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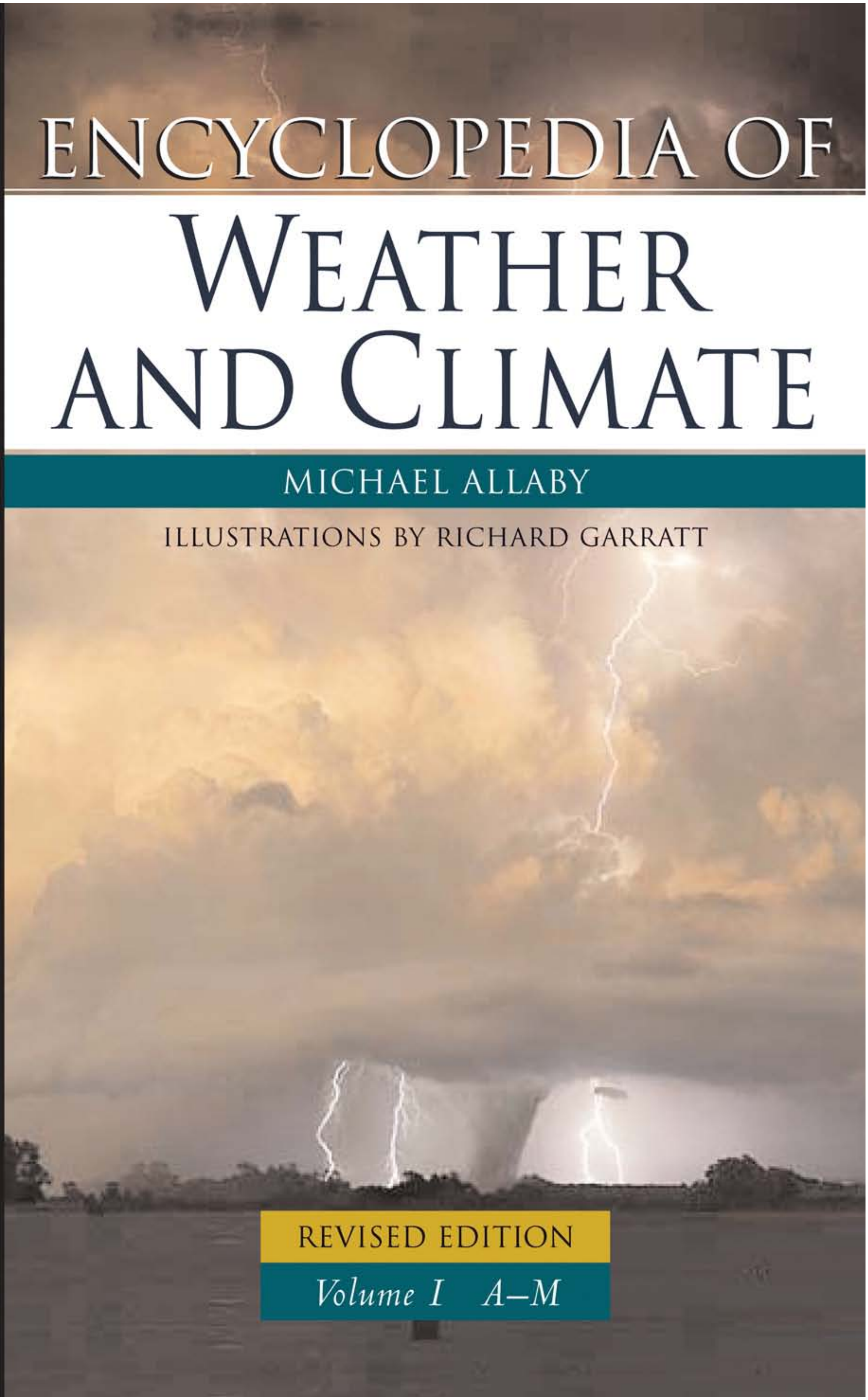

ENCYCLOPEDIA OF WEATHER AND CLIMATE

MICHAEL ALLABY

ILLUSTRATIONS BY RICHARD GARRATT

REVISED EDITION

Volume I A–M

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VOLUME I

A–O

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Contents

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My friend Richard Garratt drew all of the maps, diagrams, and other line drawings in this encyclopedia. Richard and I have collaborated on many projects, spanning more years than either of us cares to count. He has a genius for translating my crude sketches into accurate and attractive illustrations. As always, I am deeply grateful to him.

There were not many photographs in the first edition of the encyclopedia, but we decided to include them in this edition. I drew up a long list of topics I thought might benefit from a photograph and sent the list to Tobi Zausner. With great perseverance and unfailing good humor she gathered together the pictures you will see here. Without Tobi's help this would be a less informative book than it is, and one less pleasing to the eye.

Finally, I must thank my friends at Facts On File. In particular, I would like to thank my editor, Frank K. Darmstadt, for his patience, wisdom, and the kindly interest he always shows in the well-being of his author and for the polite interest he shows in the current location of the text he was supposed to have received weeks or months ago. Appreciation also goes to his assistant, Alana Braithwaite, for going through this huge manuscript and getting all of its elements in order for production to take over.

This work is not a compilation of entries written by contributors. I wrote all of the entries myself. The consequence is that any mistakes that have escaped Frank's eagle eye are entirely my own work. So are the facts I got right, of course.

Introduction

Everyone has an interest in the weather, and in recent years that interest has intensified. Climates always change over long periods. The weather the world experiences today is different from that of the Little Ice Age of the 17th century and of the Middle Ages, when the climate was warm and England was a major wine producer. Today, though, there are fears that the climate may be changing faster than it has done for thousands of years and that the gases released into the air from cars, factories, domestic fires, power stations, farming, and forest clearance may be accelerating that change. This concern is now driving climatic research.

The climate of a place or of the world is the average weather that it experiences over a long period. On a shorter timescale, the day-to-day weather affects everyone. Those who set off for school or work without a coat or umbrella may get a soaking if they forget to check before leaving home whether it is raining. In winter, when snow and ice are likely, drivers should check before setting off whether the roads are safe and, if they are, whether conditions are likely to deteriorate. Misjudgments can be serious. Snowfalls can make roads impassable, marooning people in their cars where the low temperature can kill.

Some people need to know about the coming weather in more detail. Fishermen must know whether it will be safe for them to put to sea. Sailors of all kinds need to know whether they are sailing into a severe storm and, if so, how to avoid it. Pilots need to know the speed and direction of the winds along the routes they plan to fly. These determine the time the journey will take and the amount of fuel the aircraft will consume.

Extreme weather such as tornadoes, tropical cyclones, and floods can cause widespread devastation. Lives can be saved and damage to property minimized if communities receive adequate warning and respond appropriately. The warning may be broadcast on behalf of the government by a radio or television station, but it is based on information supplied by meteorologists—the scientists who study, monitor, and forecast the weather.

There are also less immediate ways in which the weather affects people. Fine growing weather across the farmlands of the nation, with rain when it is needed and sunshine to ripen the crops, produces heavy crop yields. Food is abundant, and when a commodity is abundant its price falls. So fine weather can make food cheaper. In the same way, bad weather can lead to low yields and higher prices. Changes in food prices may make the difference between relative prosperity and hardship for the poorest members of society, and in some parts of the world bad weather may lead to famine, in which people die.

Mild winters reduce heating bills. People do not need so much energy to warm their homes as they do when the winter is hard. This makes a difference to living costs, and it also has environmental consequences. Burning fossil fuels—coal, oil, or gas—to generate electrical power, or directly for space heating, water heating, and cooking, releases by-products of combustion into the air. Some of these, such as sulfur dioxide, carbon monoxide, and unburned hydrocarbons, cause pollution.

My own interest in weather and climate began many years ago. For a short time I was a military pilot, so I was compelled to observe the weather and to respect it. I learned then that bad weather can kill and that it pays to listen to the weather forecast. More recently, my interest has developed from my studies of the environmental sciences. These include the atmospheric sciences of climatology and meteorology as well as the historical disciplines such as paleoclimatology, which is the study of the climates of the distant past.

Several years have passed since the previous edition of the *Encyclopedia of Weather and Climate* was published. Research in the atmospheric sciences is intense, and so much has happened during those years that a new edition seemed advisable. This edition contains a number of new entries, but almost all of the entries from the earlier edition have been revised. Some have been expanded and others modified to take account of recent discoveries about the atmosphere and the way it works.

The preparation of a new edition also made it possible to alter the overall structure of the encyclopedia. Many of the shorter entries in the earlier edition have been assembled into longer essays in this edition. Some short entries remain, but this edition contains a smaller number of much longer essays that incorporate all the information from the earlier edition—and often more.

Certain categories of entry have been removed altogether from the main body of the encyclopedia and are contained in 10 appendixes. The appendixes contain biographical notes on more than 120 individual scientists, as well as lists of the most severe tropical cyclones and tropical storms, tornadoes, weather disasters, and milestones in atmospheric research. The principal ocean currents are also listed alphabetically and described in an appendix. I hope that placing this material in appendixes makes it more easily accessible.

The main body of the encyclopedia contains entries describing processes such as cloud formation, atmospheric phenomena such as rainbows, and some of the techniques and instruments that are used to study the atmosphere, as well as the units of measurement that scientists use. They also explain the classification systems that are used for climate types, winds, and clouds.

The weather we experience is local. It may be raining on one side of a hill and fine on the other side. This means that from time to time many places experience weather conditions different from those in the surrounding region, and the local conditions usually have local names. Winds, in particular, acquire local names. The chinook, Santa Ana, mistral, harmattan, bora, and sirocco are just a few of the local names for winds that people in certain places welcome or dread. The encyclopedia lists some of these, in entries on local weather and local winds, and explains each type and where it occurs.

Before there were weather stations, orbiting satellites, and powerful computers to produce weather forecasts, people had to rely on their experience and the signs they could read, or thought they could read, in the sky and in the natural world around them. Over centuries these experiences accumulated as weather lore, comprising sayings, rhymes, and references to clouds, plants, and animals. Some of these are also included here, in an entry on weather lore.

Small capital letters (LIKE THIS) used within entries act as cross-references, indicating terms for which there are full entries.

Items for further reading and relevant Web sites are listed at the end of the entries to which they relate. They are also listed at the end of the encyclopedia.

Finally, a note on the units of measurement used here. Many scientific disciplines use special units to describe quantities that are relevant only within those disciplines. Atmospheric chemists, for example, use Dobson units to measure the concentration of atmospheric gases, especially of ozone. Apart from such specialist units, all scientists work in SI units. SI stands for Système International d'Unités (International System of Units). The meaning of individual units (including Dobson units) is explained in the entry "units of measurement"; SI units are listed with their abbreviations and, where appropriate, conversions to customary units.

Meteorologists measure air pressure in pascals, but weather forecasters often use the older unit, the millibar (1 millibar = 100 pascals).

Temperatures are reported in degrees Celsius (°C) or in kelvins (K), depending on the context. In this encyclopedia, temperatures are given in degrees Fahrenheit (°F) with °C in parentheses.

Rainfall is always reported in millimeters and never in centimeters. There are two reasons for this. The first is to avoid decimal fractions so far as is possible by using a small unit. The second is to avoid the confusion that might occur if two units were used, one of which is 10 times bigger than the other. In all entries in this *Encyclopedia of Weather and Climate, Revised Edition,* rainfall is given in inches with millimeters in parenthesis.

I hope you enjoy wending your way through the highways and byways of atmospheric science as you explore the processes that generate our weather. Writing the encyclopedia was fun. I hope it is fun to use.

—Michael Allaby
Tighnabruaich
Argyll, Scotland
www.michaelallaby.com

Abbreviations and Acronyms

If the meaning of an abbreviation or acronym is set in small capital letters, it occurs as an entry in its own right in the main body of the encyclopedia. If the explanation occurs within another entry, the title of that entry is written in small capitals following the explanation. For example, A is the abbreviation for *ampere*. *Ampere* does not occur as an entry, but its meaning is explained in an entry on UNITS OF MEASUREMENT.

A ampere. *See* UNITS OF MEASUREMENT.

AABW ANTARCTIC BOTTOM WATER.

AAC Antarctic Convergence. *See* ANTARCTIC POLAR FRONT.

AAO ANTARCTIC OSCILLATION.

ABW ARCTIC BOTTOM WATER.

Ac altocumulus. *See* CLOUD TYPES.

Ac_{len} lenticular cloud. *See* CLOUD TYPES.

ACE Accumulated Cyclone Energy Index. *See* TROPICAL CYCLONE.

ACW ANTARCTIC CIRCUMPOLAR WAVE.

AIW ANTARCTIC INTERMEDIATE WATER.

AMO ATLANTIC MULTIDECADAL OSCILLATION.

AO ARCTIC OSCILLATION.

APF absolute pollen frequency. *See* POLLEN.

APT automatic picture transmission. *See* SATELLITE INSTRUMENTS.

Ar ARGON.

As altostratus. *See* CLOUD TYPES.

ASOS AUTOMATED SURFACE OBSERVING SYSTEMS.

AVHRR Advanced Very High Resolution Radiometer. *See* SATELLITE INSTRUMENTS.

Bq becquerel. *See* UNITS OF MEASUREMENT.

Btu British thermal unit. *See* UNITS OF MEASUREMENT.

C coulomb. *See* UNITS OF MEASUREMENT.

cal calvus. *See* CLOUD TYPES.

CAM crassulacean acid metabolism. *See* PHOTOSYNTHESIS.

cap capillatus. *See* CLOUD TYPES.

CAPE convective available potential energy. *See* STABILITY INDEX.

cas castellanus. *See* CLOUD TYPES.

CAT CLEAR AIR TURBULENCE.

Cb cumulonimbus. *See* CLOUD TYPES.

Cc cirrocumulus. *See* CLOUD TYPES.

CCD carbonate compensation depth. *See* CARBON CYCLE.

CCN CLOUD CONDENSATION NUCLEI.

cd candela. *See* UNITS OF MEASUREMENT.

Ci cirrus. *See* CLOUD TYPES.

CISK conditional instability of the second kind. *See* STABILITY OF AIR.

CISOs Climatological Intra-Seasonal Oscillations. *See* MONSOON.

CLAES Cryogenic Limb Array Etalon Spectrometer. *See* SATELLITE INSTRUMENTS.

CLIMAP CLIMATE-LEAF ANALYSIS MULTIVARIATE PROGRAM. *See* CLIMATE: LONG-RANGE INVESTIGATION MAPPING AND PREDICTION.

COH coefficient of haze. *See* HAZE.

COHMAP COOPERATIVE HOLOCENE MAPPING PROJECT.

con congestus. *See* CLOUD TYPES.

CorF CORIOLIS EFFECT.

Cs cirrostratus. *See* CLOUD TYPES.

CTM chemical transport model. *See* CLIMATE MODEL.

Cu cumulus. *See* CLOUD TYPES.

Cu_{fra} fractocumulus. *See* CLOUD TYPES.

DALR dry adiabatic lapse rate. *See* LAPSE RATES.

DCI deep convective index. *See* STABILITY INDICES.

DD day degree. *See* ACCUMULATED TEMPERATURE.

DDA value depth-duration-area value. *See* PRECIPITATION.

DIC dissolved inorganic carbon. *See* CARBON CYCLE.

DMS dimethyl sulfide. *See* CLOUD CONDENSATION NUCLEI.

DMSP DEFENSE METEOROLOGICAL SATELLITE PROGRAM.

DOC dissolved organic carbon. *See* CARBON CYCLE.

DO event DANSGAARD-OESCHGER EVENT.

DOW Doppler on Wheels. *See* RADAR.

DU Dobson unit. *See* UNITS OF MEASUREMENT.

DVI dust veil index. *See* LAMB'S DUST VEIL INDEX.

EAIS East Antarctic Ice Sheet. *See* ANTARCTIC ICE SHEET.

EBM energy balance model. *See* CLIMATE MODEL.

ELR environmental lapse rate. *See* LAPSE RATES.

ENIAC Electronic Numerical Integrator and Calculator. *See* COMPUTER.

ENSO El Niño–Southern Oscillation. *See* ENSO.

EOS EARTH OBSERVING SYSTEM.

EPS Eumetsat Polar System. *See* EUMETSAT.

ERBE EARTH RADIATION BUDGET EXPERIMENT.

ERBS Earth Radiation Budget Satellite.

ERTS Earth Resources Technology Satellite. *See* Landsat.

ESMR electrically scanning microwave radiometer. *See* satellite instruments.

ESRL Earth System Research Laboratory. *See* Global Systems Division.

F farad. *See* units of measurement.

fib fibratus. *See* cloud types.

FIDO Fog Investigation Dispersal Operations. *See* fog.

flo floccus. *See* cloud types.

fra fractus. *See* cloud types.

(GAC) Global Area Coverage Oceans Pathfinder Project.

GARP Global Atmospheric Research Program.

GCOS Global Climate Observing System. *See* World Weather Watch.

GDP Global Drifter Program.

GDPFS Global Data-Processing and Forecasting Systems. *See* World Weather Watch.

GEF Global Environment Facility.

GEMS Global Environmental Monitoring System.

GEOSS Global Earth Observation System of Systems.

GERB Geostationary Earth Radiation Budget. *See* satellite instruments.

GHOST Global Horizontal Sounding Technique.

GIMMS Global Inventory Monitoring and Modeling Systems.

GISP Greenland Ice Sheet Project.

GMT Greenwich Mean Time. *See* universal time.

GOES Geostationary Operational Environmental Satellite.

GOS Global Observing System. *See* World Weather Watch.

GRID Global Resource Information Database.

GRIP Greenland Icecore Project.

GSD Global Systems Division.

GTS Global Telecommunication System. *See* World Weather Watch.

GWE Global Weather Experiment. *See* Global Atmospheric Research Program.

GWP Greenhouse warming potential. *See* greenhouse effect.

H henry. *See* units of measurement.

HALOE Halogen Occultation Experiment.

HRDI high-resolution Doppler interferometer. *See* satellite instruments.

HRPT high-resolution picture transmission. *See* satellite instruments.

hum humilis. *See* cloud types.

Hz hertz. *See* units of measurement.

IETM Initial Eocene Thermal Maximum. *See* Paleocene–Eocene thermal maximum.

IFR instrument flight rules. *See* flying conditions.

IGBP International Geosphere-Biosphere Program.

IJPS Initial Joint Polar System.

INDOEX Indian Ocean Experiment.

IPCC Intergovernmental Panel on Climate Change.

IPG International Phenological Gardens.

ISAMS improved stratospheric and mesospheric sounder. *See* satellite instruments.

ISCCP International Satellite Cloud Climatology Project.

ISLSCP International Satellite Land Surface Climatology Project.

ISOW Iceland Scotland Overflow Water. *See* North Atlantic Deep Water.

ITCLP International Tropical Cyclone Landfall Programme. *See* World Meteorological Organization.

ITCZ Intertropical Convergence Zone.

J joule. *See* units of measurement.

JDOP Joint Doppler Operational Project. *See* Doppler radar.

JNWP Joint Numerical Weather Prediction Unit. *See* weather forecasting.

K kelvin. *See* units of measurement.

K K index. *See* stability indices.

kg kilogram. *See* units of measurement.

Kr krypton.

L Avogadro constant. *See* Avogadro's law.

LAI Leaf area index.

len lenticularis. *See* cloud types.

LI lifted index. *See* stability indices.

LIDAR light detection and ranging.

lm lumen. *See* units of measurement.

LMA leaf margin analysis.

lx lux. *See* units of measurement.

ly langley. *See* units of measurement.

m meter. *See* units of measurement.

mb millibar. *See* units of measurement.

MCR mutual climatic range. *See* beetle analysis.

MCSST multichannel sea-surface temperature. *See* satellite instruments.

med mediocris. *See* cloud types.

milli atm cm milli atmospheres centimeter. *See* units of measurement.

MJO Madden-Julian Oscillation.

MLS microwave limb sounder. *See* SATELLITE INSTRUMENTS.
mol mole. *See* UNITS OF MEASUREMENT.
N newton. *See* UNITS OF MEASUREMENT.
N NITROGEN.
N_A Avogadro constant. *See* AVOGADRO'S LAW.
NADW NORTH ATLANTIC DEEP WATER.
NAO NORTH ATLANTIC OSCILLATION.
NDVI NORMALIZED DIFFERENCE VEGETATION INDEX.
Ne NEON.
neb nebulosus. *See* CLOUD TYPES.
NEXRAD NEXT GENERATION WEATHER RADAR.
NHC NATIONAL HURRICANE CENTER.
NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION.
NO_x NITROGEN OXIDES.
NRM scale Northern Rocky Mountain wind scale. *See* BEAUFORT WIND SCALE.
Ns Nimbostratus. *See* CLOUD TYPES.
NSIDC NATIONAL SNOW AND ICE DATA CENTER.
NSSL NATIONAL SEVERE STORMS LABORATORY.
O OXYGEN.
OLS operational linescan system. *See* SATELLITE INSTRUMENTS.
Pa pascal. *See* UNITS OF MEASUREMENT.
PAN peroxyacetyl nitrate. *See* AIR POLLUTION.
PDO PACIFIC DECADAL OSCILLATION.
PDSI Palmer Drought Severity Index. *See* DROUGHT.
PETM PALEOCENE-EOCENE THERMAL MAXIMUM.
PGF PRESSURE GRADIENT FORCE.
PHDI Palmer Hydrological Drought Index. *See* DROUGHT.
PIOCW PACIFIC- AND INDIAN-OCEAN COMMON WATER.
PMO port meteorological officer. *See* VOLUNTARY OBSERVING SHIP.
PO.DAAC PHYSICAL OCEANOGRAPHY DISTRIBUTED ACTIVE ARCHIVE CENTER.
PPR photopolarimeter-radiometer. *See* SATELLITE INSTRUMENTS.
PROFS PROGRAM FOR REGIONAL OBSERVING AND FORECASTING SYSTEMS.
PSCs POLAR STRATOSPHERIC CLOUDS.
PSI Pollution Standards Index. *See* AIR POLLUTION.
PWSP Public Weather Services Program. *See* WORLD WEATHER WATCH.
QBO QUASI-BIENNIAL OSCILLATION.
RAINEX hurricane rainband and intensity change experiment. *See* TROPICAL CYCLONE.
RAPID Rapid Climate Change. *See* RAPID.
rad radian. *See* UNITS OF MEASUREMENT.

Re Reynolds number.

RH relative humidity. *See* humidity.

RI rainfall index. *See* National Rainfall Index.

RMS root-mean-square.

Rn radon.

Ro Rossby number.

ROFOR route forecast. *See* weather forecasting.

ROFOT route forecast. *See* weather forecasting.

ROMET route forecast. *See* weather forecasting.

RPF relative pollen frequency. *See* pollen.

S sulfur.

SAGE stratospheric aerosol and gas experiment. *See* satellite instruments.

SALR saturated adiabatic lapse rate. *See* lapse rates.

SAR synthetic aperture radar. *See* radar.

Sc stratocumulus. *See* cloud types.

SELS Severe Local Storms unit.

SI units Système International d'Unités. *See* Appendix ix: SI Units and Conversions.

SMMR scanning multichannel microwave radiometer. *See* satellite instruments.

SOA secondary organic aerosol. *See* aerosol.

SOI Southern Oscillation Index. *See* Southern Oscillation.

SPI standardized precipitation index. *See* drought.

spi spissatus. *See* cloud types.

sr steradian. *See* units of measurement.

SSI Showalter Stability Index. *See* stability indices.

SSM/I special sensor microwave imager. *See* satellite instruments.

St stratus. *See* cloud types.

START Global Change System for Analysis Research and Training. *See* International Geosphere-Biosphere Program.

s.t.p. standard temperature and pressure. *See* units of measurement.

str stratiformis. *See* cloud types.

T tesla. *See* units of measurement.

TAFB Tropical Prediction Center.

TAO Tropical Atmosphere Ocean.

TEMPO Testing Earth System Models with Paleoclimatic Observations. *See* Cooperative Holocene Mapping Project.

THI temperature-humidity index. *See* comfort zone.

TIROS Television and Infrared Observation Satellite.

TLV threshold limit value. *See* pollution control.

TM thematic mapper. *See* satellite instruments.

TOGA Tropical Ocean Global Atmosphere.

TOMS Total Ozone Mapping Spectrometer. *See* SATELLITE INSTRUMENTS.

TOTO TOTABLE TORNADO OBSERVATORY.

TPC TROPICAL PREDICTION CENTER.

TSB Technical Support Branch. *See* TROPICAL PREDICTION CENTER.

UARS UPPER ATMOSPHERE RESEARCH SATELLITE.

unc uncinus. *See* CLOUD TYPES.

UNEP UNITED NATIONS ENVIRONMENT PROGRAMME.

UT UNIVERSAL TIME.

UTC Coordinated Universal Time. *See* UNIVERSAL TIME.

UV ULTRAVIOLET RADIATION.

UVI ULTRAVIOLET INDEX.

V volt. *See* UNITS OF MEASUREMENT.

VEI VOLCANIC EXPLOSIVITY INDEX.

VFR visual flight rules. *See* FLYING CONDITIONS.

VOS VOLUNTARY OBSERVING SHIP.

W watt. *See* UNITS OF MEASUREMENT.

WAIS West Antarctic Ice Sheet. *See* ANTARCTIC ICE SHEET.

Wb weber. *See* UNITS OF MEASUREMENT.

WCP WORLD CLIMATE PROGRAM.

WINDII wind imaging interferometer. *See* SATELLITE INSTRUMENTS.

WMO WORLD METEOROLOGICAL ORGANIZATION.

WWW WORLD WEATHER WATCH.

Z Greenwich Mean Time. *See* UNIVERSAL TIME.

Entries A–O

A

ablation The removal of ice and snow from the ground surface by melting and also by the process of SUBLIMATION. It is the most important mechanism for removing ice and snow in regions where the air temperature remains below freezing for extended periods. An area in which the rate of loss of ice by ablation, and by iceberg calving from a glacier, exceeds the rate at which new snow and ice accumulates is known as the ablation zone.

absorption A process by which one substance takes up and retains another to form a liquid or gaseous solution, or the transfer of energy from electromagnetic radiation to atoms or molecules that it strikes. Certain gases are absorbed by ACTIVATED CARBON, which is used to reduce air pollution. Ultraviolet radiation is absorbed by atmospheric gas molecules.

The substance that takes up the other is known as the absorbate, and the substance that is held is the absorbent.

Desorption is the release of a gas that had previously been held in or on the surface of another substance. It is the opposite of both absorption and ADSORPTION.

absorption of radiation A response to exposure to electromagnetic radiation in which energy is transmitted to molecules, causing them to vibrate more vigorously or to move faster. This process converts radiation energy into KINETIC ENERGY, which is dissipated among the surrounding molecules and converted into heat.

It is the absorption of solar radiation that warms the surface of the Earth and contact with the warmed surface that warms the atmosphere and drives the GENERAL CIRCULATION, thereby producing all weather phenomena. Some radiation is also absorbed by components of the atmosphere.

The proportion of radiation that a material absorbs is known as the absorptivity of that material, and it is the ratio of the amount of radiation that is absorbed to the amount that would be absorbed by a BLACKBODY. This is equal to the reciprocal of the value of the ALBEDO of that material.

Most surface materials absorb radiation at all wavelengths, but certain molecules absorb radiation only at particular wavelengths. Water vapor absorbs at 5.3–7.7 m and beyond 20 μm, carbon dioxide at 13.1–16.9 μm, and ozone at 9.4–9.8 μm, for example.

Below a height of about 44 miles (70 km) materials are in thermodynamic equilibrium, and according to KIRCHHOFF'S LAW, they both absorb and emit radiation at the same wavelength. The amount of radiation they emit depends on their EMISSIVITY.

absorption tower A structure in which a solid or liquid absorbs another gas or liquid that is passed through it. The device is commonly used to remove pollutants from a stream of waste gases before these are discharged into the outside air. Sulfur dioxide (SO_2) and sulfur trioxide (SO_3) are absorbed by water to form sulfuric acid (H_2SO_4) that can be recovered, for example. Volatile organic compounds, including xylenes, which are released when ships are loaded with petroleum, can also be recovered in absorption towers. Their absorption reduces pollution and the xylenes can be used, because they are raw materials for several industrial processes.

acceleration A rate of change of speed or VELOCITY that is measured in units of distance multiplied by the square of a unit time, such as feet per second per second (ft/s^2) or meters per second per second (m/s^2).

For a body that is moving in a straight line and accelerating at a constant rate from a speed u to a speed v, the acceleration (a) is given by: $a = (v - u)/t$, where t is the time taken, and $a = (v^2 - u^2)/2s$, where s is the distance covered.

acclimatization An adaptive, physiological response that allows an animal to tolerate a change in the climate of the area in which it lives. In addition to changes in temperature and precipitation, climatic change also affects the availability of food and sometimes of nesting sites and materials.

The most obvious examples of acclimatization occur as animals adjust to the changing seasons. For example, as temperatures fall with the approach of winter, in many animals the cells produce additional enzymes that help to compensate for the reduced activity of enzymes at low temperatures.

Some animals are able to tolerate extremely low temperatures, providing the temperature falls slowly enough for them to adjust. There are insects, such as the parasitic wasp *Bracon cephi,* that convert glycogen to glycerol. This acts as "antifreeze" by lowering the freezing temperature of body fluids. *Bracon cephi* can survive at temperatures below -4°F (-20°C). Certain fish can produce trimethylamine, which has a similar effect to glycerol. Blood plasma in the Greenland or Labrador cod (*Gadus ogac*) freezes at 30.6°F (-0.8°C) in summer, but at 29.1°F (-1.6°C) in winter. Metabolic rate may also increase as the temperature falls.

Tolerance of high temperatures also varies seasonally. The brown catfish, also called the brown bullhead (*Ictalurus nebulosus*), found from southern Canada through most of the United States, is likely to die if the water temperature in August exceeds 96°F (35.8°C). In October it can tolerate only 88°F (31°C), and it may die in winter if it is exposed to temperatures higher than 84°F (29°C).

Mammals living in high latitudes grow thicker fur, and in some species, such as the arctic fox (*Alopex lagopus*) and blue hare (*Lepus timidus*), the fur changes color from brown to white to provide camouflage in a snow-covered landscape. Behavioral changes may also take place, as when animals prepare for and enter hibernation and later emerge from it. Acclimatization also occurs when an animal migrates from one region to another with a different climate. In humans moving to a warmer climate, the rate of sweating increases over several days until a new balance is struck that produces a comfortable level of cooling.

A response by an animal that allows it to tolerate a change in a single factor in its environment, such as temperature, is called acclimation. Environmental changes seldom occur singly, and acclimation is usually measured only under controlled conditions in the laboratory.

accumulated temperature The sum of the amount (the number of degrees) by which the air temperature rises above or falls below a particular DATUM level over an extended period. The datum level is usually set at a value that is relevant to crop production or to an ecological study.

If, on a particular day, the mean temperature is m degrees above (or below, in which case it has a negative value) the datum level and it remains so for n hours (= $n/24$ days), then the accumulated temperature for that day is $mn/24$. Adding the accumulated temperatures for each day yields the accumulated degree-days temperature for a week, month, season, or year.

When the concept is applied to agriculture or horticulture, degree days are calculated against a datum level that is equal to the minimum temperature needed for growth—called the zero temperature—for a particular crop plant. The number of degree days with a positive value (indicating that the temperature is high enough for the crop to grow) indicates the time it will take for a crop plant to mature. The zero temperature for corn (maize), for example, is about 55°F (12.8°C), and in northern Utah corn requires 1,900–2,600 degree days. The sum of all the individual degree days is called the total degree-days.

The degree day concept is similar to that of the day degree (DD). Day degree values are calculated by multiplying together the number of days (rather than hours, as in the case of the degree day) on which the mean temperature is above or below a particular datum level by the number of degrees by which it deviates from the datum level. Plants and many animals, especially invertebrate animals, are able to grow and reproduce only when the temperature is above a certain threshold. Consequently, their development is directly related to the length of time during which the temperature exceeds that threshold. Calculating the number of day degrees allows scientists to predict the date when a crop plant will be ready to harvest and also the date when particular insect pests will emerge.

The temperature below which almost no plant growth occurs is known as the cardinal temperature. Cardinal temperatures are used in conjunction with accumulated temperatures to evaluate crop growth in the course of a growing season.

accumulation The extent by which the thickness of a layer of snow or ice increases over time through the addition of new snow or ice. It represents the amount of material added, minus the amount lost during the same period through ABLATION.

acid deposition The placing (depositing) onto surfaces of airborne substances that are more acid than the naturally occurring constituents of clean air. This is usually a consequence of pollution from natural sources or, more commonly, from industrial or vehicle emissions and from domestic coal-burning fires (where these are still permitted). ACIDITY is measured on a pH scale where pH 7.0 is neutral, values below 7.0 are acid, and values above 7.0 are alkaline.

Acid rain is rain that is more acidic than unpolluted rain as a result of contamination by emissions from such sources as power plants, factories, vehicle exhausts, forest and bush fires, and volcanic eruptions. "Acid rain" is a blanket term that is used to describe the cause of all damage by acid pollution, but damage is less likely from acid rain than from other forms of acid deposition. This is because rain runs off surfaces quickly, so they are exposed to the acid for only a very short time.

Ordinary, unpolluted rain has a pH of about 5.6. It is naturally acid, because it contains acid solutions of certain atmospheric gases. CARBON DIOXIDE (CO_2) dissolves into it to produce carbonic acid (H_2CO_3); nitrogen is oxidized by the energy of LIGHTNING and the oxides dissolve to form nitrous (HNO_2) and nitric (HNO_3) acids; and naturally occurring sulfur dioxide (SO_2) is oxidized and dissolved to form sulfuric acid (H_2SO_4). Acid rain has a pH value of less than 5.0.

Although acid rain is commonly thought to be the principal means by which acid deposition occurs, it is not the only one and it is the least serious in its effects. Acid mist is more damaging than acid rain, because mist droplets are so small that they drift horizontally and fall only very slowly. Consequently, they coat all exposed surfaces, rather than only the upper surfaces that are exposed to falling rain. Acid mist keeps the surfaces wet, allowing ample time for chemical reactions to take place.

The process of depositing acid onto the surfaces of plants, buildings, and other objects that takes place when they come into direct contact with mist or CLOUD DROPLETS containing dissolved acid is called occult deposition.

Acid snow is also more harmful than acid rain, but for a different reason. Snow accumulates, and while it covers surfaces, any acid it contains can have little effect because the surfaces are exposed only to the snow layer that is in direct contact with them, and reactions proceed very slowly, if at all, at temperatures below freezing. When the snow melts, however, its acid is released, often fairly slowly, onto surfaces and also into the ground, where it can affect soil chemistry.

The term acid precipitation describes all forms of wet acid deposition—acid rain, acid mist, and acid snow.

Dry deposition is probably the most harmful type of acid deposition. This involves the transfer of particles from dry air to a surface onto which they are adsorbed (*see* ADSORPTION). Dry deposition occurs when the turbulent flow of air brings the particles into contact with the surface, and the rate at which this takes place can be calculated to give the deposition velocity. Particles or molecules that are adsorbed onto leaves may then be absorbed (*see* ABSORPTION) into plant cells through the stomata (*see* PHOTOSYNTHESIS).

The report of a study in the Los Angeles area, published in 1980, found that dry deposition of acid pollutants was 15 times more important than wet deposition, or acid rain, in the harm it caused to vegetation.

Acid soot, also called acid smut, is a variety of dry deposition involving particles of soot, approximately 0.04–0.12 inch (1–3 mm) in diameter, that are bound together by water that has been acidified. The acidification is due to a reaction between water (H_2O) and sulfur trioxide (SO_3) present in the waste gases accompanying the soot particles, to form sulfuric acid (H_2SO_4). Acid soot tends to cling to solid surfaces and is corrosive. It is a by-product of the inefficient burning of oil or coal with a high sulfur content.

Acidification as a result of pollution was first reported in 1852, in an area downwind from the industrial city of Manchester, in northwestern England. Cases were also well documented from copper smelters at Trail, British Columbia, Canada, from 1896 until 1930, and early in the 20th century at Anaconda, Montana.

Acid deposition emerged again as a problem in the 1960s. This time, the pollution was experienced not close to its source, as had been the case earlier, but over very much larger areas. Earlier attempts to reduce AIR POLLUTION from industrial sources had been based on dilution. Smokestacks had been built much taller, and they were modified to accelerate the gases and particles rising through them so the emissions entered the air traveling at considerable speed. This carried them higher, the idea being that as they drifted downwind they would be greatly diluted by mixing with the surrounding air. Conditions improved near the pollution sources, but the improvement extended no farther than about 100 miles (160 km) downwind. Today, it is accepted that the contamination causing acid rain can be reduced effectively only by reducing the emissions responsible for it.

During the 19th and 20th centuries acid deposition caused serious erosion to limestone buildings and statues, and in the 1960s and 1970s it was blamed for widespread damage in the forests of Central Europe, the phenomenon German environmentalists called Waldsterben. It was also associated with the pollution of lakes, especially in Scandinavia.

Waldsterben is the name given to the damage in German forests that was attributed to acid rain. The word means “forest death” and at first was attributed to sulfur dioxide transported by rain. This proved not to be the cause, however. Lichens that are highly intolerant of sulfur grew abundantly in the damaged forests. Gradually, the term *Waldsterben* fell from use as the condition of forest trees came to be better understood.

Damage to buildings certainly occurred, but the effect on plants and lakes was found to be much smaller than had first been reported, and the causes of it proved to be much more complicated. Drought and disease also affected forests. The proportion of damaged trees was revised from more than 50 percent to less than 20 percent when the method of measuring it was standardized, and the extent of damage varied with the type of soil. This does not mean there was no problem, however. Although the effect was smaller than had been feared, acid deposition certainly contributed to a deterioration in the health of American and European forests.

Acid deposition did cause real harm, and measures have been taken in most countries to reduce the emissions of nitrogen and sulfur oxides that produce it. Recovery from its effects is slow, but it has begun and will continue, provided emissions remain under control.

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acidity According to the theory published in 1923 by the Danish physical chemist Johannes Nicolaus Brønsted and the British chemist Thomas Lowry, who were working independently of each other, a measure of the extent to which a substance releases hydrogen IONS (protons) when it is dissolved in water. Also in 1923, the American theoretical chemist Gilbert Newton Lewis defined acidity as the extent to which a substance acts as receptor for a pair of electrons from a base. The two theories describe different ways of looking at the same thing and do not contradict each other.

Acidity is measured on a scale of 0–14, which was introduced in 1909 by the Danish chemist Søren Peter Lauritz Sørensen. The acidity of a solution, measured at 25°C (77°F), is equal to the negative logarithm of c ($-\log_{10}c$), where c is the concentration of hydrogen ions in moles per liter. The scale measures the “potential of hydrogen,” which is abbreviated to pH, so it is known as the pH scale.

A neutral (neither acid nor alkaline) solution has a hydrogen-ion concentration of 10^{-7} mol l^{-1}, so it has a pH of 7. A pH lower than 7 indicates an acid solution and one higher than 7 an alkaline solution. The scale is logarithmic, so a difference of one whole number in pH values indicates a tenfold difference in acidity. A carbonated soft drink has an acidity of about pH 3, making it 10,000 times more acid than distilled water (pH 7), and ammonia (pH 12) is 100,000 times more alkaline than distilled water.

activated carbon **(activated charcoal)** Carbon that has been treated to make it highly absorbent to gases and to some COLLOIDS. The carbon is obtained by heating fresh plant material, lignite (brown coal), bituminous coal, or anthracite in the presence of a solution of a substance such as zinc chloride (ZnCl) or phosphoric acid (H_3PO_4) that dissolves the material and catalyzes the reaction. This process is known as pyrolysis, and it yields pellets of carbon. If the carbon is derived from coal, additional processing is needed.

The carbon is then heated by exposing it to steam or carbon dioxide in a greatly reduced supply of air, raising its temperature to 1,470°-1,830°F (800°–1,000°C). Heating activates the carbon by making the surface of the pellets highly porous. Activated carbon is used in gas masks, to remove odors from air, and in various devices for reducing air pollution.

The activated carbon process is a method that was invented in Japan for removing sulfur dioxide (SO_2) from flue gases and that is now widely used. There are three ways the SO_2 can be removed, called water washing, gas desorption, and steam desorption.

In the water washing process the gas is passed through activated carbon, and the SO_2 is absorbed. The activated carbon is then washed with water. This removes the SO_2 as sulfuric acid (H_2SO_4) or, if limestone or chalk (both are calcium carbonate, $CaCO_3$) are mixed with the carbon, as gypsum ($CaSO_4.2H_2O$).

In the gas desorption process the SO_2 is absorbed onto activated carbon and then released (desorbed) as SO_2.

The steam desorption process is similar, but steam is used to desorb the SO_2.

active instrument An instrument that sends out a signal that is reflected back to it. Instruments that use RADAR and lidar are active.

actual elevation The vertical distance between sea level and a weather station.

adfreezing The process by which two objects stick to each other because a layer of water freezes between them. The word is derived from adhesion and freezing. Objects can become frozen to the ground with a degree of firmness that is known as the adfreezing strength.

adiabat The rate at which a PARCEL OF AIR cools as it rises (and warms as it descends). It is shown on a TEPHIGRAM as two lines, one representing the dry adiabat and the other the saturated adiabat. The dry adiabat is also a line of constant POTENTIAL TEMPERATURE (an isentrope).

Adiabatic is the adjective describing a change of temperature that involves no addition or subtraction of heat from an external source. The word is from the Greek *adiabatos,* which means "impassable," suggesting that the substance in which adiabatic temperature changes occur is isolated from its surroundings.

Air close to the ground is subject to DIABATIC TEMPERATURE CHANGE, but air that is above this surface layer and moving vertically warms and cools adiabatically. The phenomenon is simple to demonstrate. When a bicycle tire is inflated vigorously using a hand pump, the barrel of the pump and the valve on the tire become warm. This is because the air is being compressed inside the barrel and at the valve, and when air is compressed its temperature increases. If the valve of a bicycle tire is released, the air that rushes out feels cool. This is because the air is expanding, and when air expands its temperature decreases. The air in the pump and tire has not been warmed or cooled from outside—the temperature change is adiabatic.

Adiabatic temperature change is a version of the first law of THERMODYNAMICS that can be stated as:

temperature change = pressure change × a constant.

Compression means that a given number of molecules are forced to occupy a smaller volume. In other words, the molecules are packed more closely together as a result of external pressure. Energy is required to compress air—you must do work to pump up a tire—and some of that energy is absorbed by the molecules. Having more energy, they move faster and collide with one another more violently and, because they are closer together, more often. A THERMOMETER measures this change in the behavior of the molecules as a rise in TEMPERATURE.

When the substance expands, its molecules expend energy in pushing one another aside so each of them occupies a larger volume. As they lose energy, they slow down. Collisions between them become less frequent, because the molecules are farther apart, and less violent because the molecules are traveling more slowly. This change is measured as a fall in temperature.

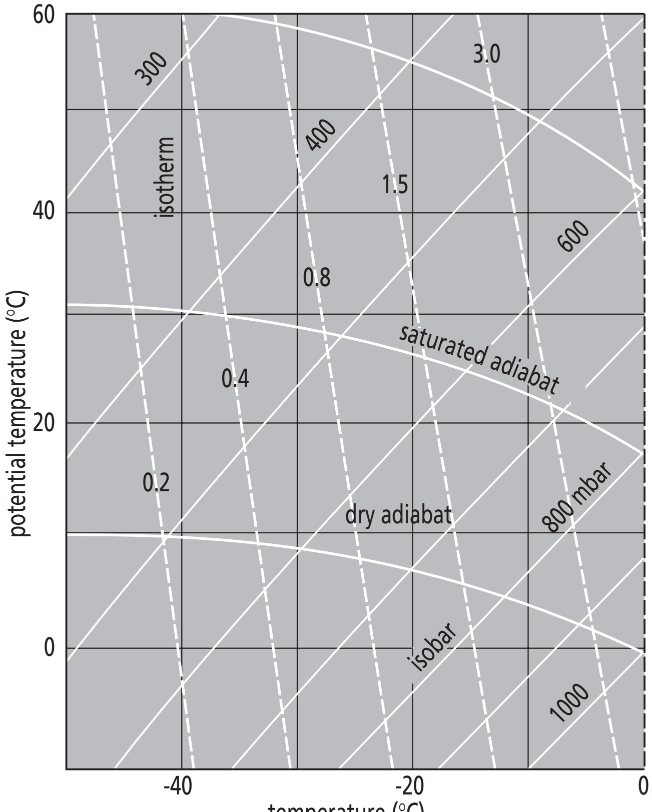
Air experiences large adiabatic temperature changes because it is very compressible and it is also a poor conductor of heat. AIR PRESSURE decreases with height, so a parcel of air that moves vertically experiences a constant change in pressure and its compressibility allows it to expand or contract accordingly. Because it is a poor conductor of heat, there is little exchange of heat between a moving parcel of air and the larger body of air through which it passes, so the parcel tends to retain its thermal characteristics. The rate at which the temperature of air changes adiabatically with height is a constant, known as the LAPSE RATE.

All fluids are subject to adiabatic temperature changes, but the changes in liquids are very much smaller than the changes in gases, because gases are very much more compressible than liquids. In the oceans, the adiabatic temperature change below the surface layer of well-mixed water is usually less than 0.1°F for every 1,000 feet (0.2°C per km).

A theoretical atmosphere in which the temperature decreases at the dry adiabatic lapse rate throughout the whole of its vertical extent is called an adiabatic atmosphere.

The continuous rate at which the temperature of dry air changes with height adiabatically is known as the dry adiabat. It is a sequence of states, each of which is defined by temperature and pressure. Dry adiabats are shown on THERMODYNAMIC DIAGRAMS. On a tephigram, they appear as straight lines that are also isotherms of POTENTIAL TEMPERATURE.

The saturated adiabat (also called the moist adiabat and wet adiabat) is a line on a tephigram that marks the constant wet-bulb potential temperature. It makes an angle of about 45° to the dry adiabat in the lower troposphere, but at lower temperatures and pressures it approaches the dry adiabat until the two are almost, but never quite, parallel.



The saturated adiabat, shown here, marks the line of constant wet-bulb potential temperature.

adsorption The chemical or physical bonding of molecules to the surface of a solid object or, less commonly, of a liquid. The adsorbed molecules form a layer on the surface. If they are attached by chemical bonds, the process is known as chemisorption; if they are held physically, by van der Waals' forces, the process is physisorption.

The substance that is absorbed is called the absorbate, and the substance holding it is the adsorbent. Adsorbents are often used to remove pollutants from industrial waste gases.

Desorption is the release of a gas that had previously been held in or on the surface of another substance. It is the opposite of both ABSORPTION and adsorption.

advection A change in temperature that is caused by the movement, usually horizontal, of air or water. A warm breeze that raises the temperature on what had been a cool day is an example of a heat transfer by advection, and the movement of warm air over cold ground can produce advection fog (*see* FOG). Winds of the FÖHN type also transfer heat by advection. The transfer of heat by warm and cool ocean currents is also an example of advection, in which the Gulf Stream and Kuroshio Current are especially important (*see* APPENDIX IV: OCEAN CURRENTS).

In addition to the transfer of sensible heat—heat that can be felt and measured as a change in temperature—LATENT HEAT can also be transported by advection. Water vapor that condenses out of warm air that is chilled by crossing a cold surface releases the latent heat of condensation.

As air moves horizontally, its characteristics are modified by the surfaces with which it comes into contact. These advective effects on the moving air are of three types, known as the clothesline effect, leading-edge effect, and oasis effect.

The clothesline effect occurs when warm, dry air enters and flows through vegetation, such as a forest or farm crop. Near the edge, the moving air raises the temperature of the surfaces it encounters, which increases the rate of evaporation from those surfaces. This has a drying effect on the soil. Farther into the vegetation stand, the temperature of the air falls, raising its relative HUMIDITY.

As moving air encounters new surface conditions, the air that is in immediate contact with the surface is affected, but the air behind or above this BOUNDARY LAYER is not. The localization of the exchange of heat between surface and air produces a leading-edge effect, in which the altered boundary layer spreads downwind with only its lower part fully adjusted to the new conditions. Above this lowest layer the air is partly changed by the new conditions, but above the boundary layer it is the air above the moving air, not the surface below, that determines the characteristics of the air. Because the leading edge extends downwind over a distance or fetch, this is sometimes called the fetch effect. A leading-edge effect always occurs where air moves from one surface to another surface that is markedly different, such as between land and water, or dry and irrigated farm land.

The oasis effect occurs because moist ground is always cooler than adjacent dry ground, a phenomenon that is most clearly observed in a desert oasis. Over ground in a dry climate that is kept moist either by irrigation or because the water table is at or above ground level, the rate of evaporation exceeds the rate of precipitation, and the warm air over the ground supplies the latent heat of vaporization. In the surrounding area, which is dry, evaporation and precipitation balance, but because the amount of precipitation is low, the rate of potential evaporation exceeds that of precipitation. Surplus heat is absorbed by the ground and warms the air in contact with the surface. This produces a large BOWEN RATIO over the dry ground and a negative Bowen ratio over the moist ground. The difference in temperature is reflected in a local difference in surface pressure, producing a situation in which air is subsiding over the moist ground and rising over the dry ground. The oasis effect occurs not only at desert oases, but also in other places, such as where irrigated cropland is adjacent to unirrigated, dry ground, in a city park surrounded by streets and buildings, or over a lake in a dry region. Downwind of the oasis, the air is moister and cooler and will cool the ground that it crosses, completing the oasis effect.

aeroallergen An airborne particle or substance to which sensitive people are allergic. Aeroallergens make such persons sick and therefore they benefit from the regular monitoring and reporting of allergen concentrations. These vary according to the weather conditions.

Rain washes aeroallergens from the air, so concentrations increase in dry weather. They also increase when air is trapped beneath an INVERSION. The principal allergens are plant POLLEN grains. These are released when the wind-pollinated source plants are in flower and are absent at other times of year. Those pollens causing the majority of adverse reactions are from grasses (family Poaceae), ragweed (*Artemisia* species), hazel (*Corylus* species), cypress (*Cupressus* species), alder (*Alnus* species), birch (*Betula* species), and hornbeam (*Carpinus* species). Fungal spores, most of which are released in the fall, can also cause allergic reactions.

Further Reading

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aerobiology The scientific study of airborne particles that are of biological origin. This involves studying the sources of such particles, the way they disperse, the distances they travel and time they remain aloft, and the surfaces on which they are deposited. Interest in the subject began in the 1960s, and there are now national aerobiological associations, most of which are affiliated to an international organization.

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aerodynamic roughness Irregularities in a surface that impede the passage of air and significantly reduce the wind speed. Close to the surface the size, shape, and distribution of the irregularities determine the wind speed. With the exception of water when there are no waves and very little wind, all surfaces are aerodynamically rough to a greater or lesser extent.

Surface roughness reduces the WIND SPEED from the surface up to a height equal to 1–3 times the height of the projecting elements causing the roughness, the magnitude of the effect decreasing with height. If the reduction in wind speed from the top of the affected BOUNDARY LAYER is continued downwards, a height will be reached at which the wind speed is reduced to zero. This is known as the roughness length (usually represented as z_0). Provided the projecting elements do not bend in the wind and thereby reduce the friction, z_0 can be calculated from the height of the elements by:

$$\log z_0 = a + b \log h$$

where h is the height of the elements in centimeters and a and b are constants. Estimates of the value of the constants vary, but two values that are commonly used are $a = -1.385$ and $b = 1.417$. Using these values, in a fir forest where the trees are 555 cm (18 feet) tall, z_0 = 283 cm (9.3 feet); in a large city (in fact Tokyo), z_0 = 165 cm (5.4 feet); in grass about 6 cm (2.4 inches) tall z_0 = 0.75 cm (0.3 inch); and over a tarmac surface z_0 = 0.002 cm (0.0008 inch).

aeronomy The scientific study of the atmosphere and of the changes that occur within it as a consequence of internal or external influences. The study embraces the composition of the atmosphere, relative movements of air within it, the transport of energy, and the radiant energy that powers these processes. Aeronomical findings, especially those from the middle and upper atmosphere, are also applicable to the atmospheres of other planets and solar-system satellites.

aerosol A mixture of solid or liquid particles that are suspended in the air. Strictly speaking, a cloud, comprising water droplets, ice crystals, or a mixture of both suspended in air is an aerosol. The word is more usually applied to solid particles, however, and the term *lithometeor* describes any solid particle that is suspended in or transported by the air. Airborne DUST particles, sand grains, and SMOKE particles are lithometeors.

Aerosol particles are so small that gravity has little effect on them. They range in size from around one-thousandth of a micron (10^{-3} μm) to about 10μm, those between 0.1μm and 10μm being considered large. Particles less than 0.1μm in size are known as Aitken nuclei. Aerosol particles fall naturally at a rate of about 4 inches (10 cm) a day, but they are removed much more quickly by being washed from the air by rain or snow.

Aerosols consist of soil particles, dust (some of which enters from space), salt crystals from the evaporation of water from drops of sea spray, smoke, aerial plankton, and organic substances. The photooxidation (*see* PHOTODISSOCIATION: PHOTOLYTIC CYCLE) of volatile organic compounds produces other organic compounds, some of which are volatile and some not. These contribute to the formation of secondary organic aerosol (SOA) particles. For example, toluene and xylenes are volatile compounds present in gasoline that are responsible for the formation of SOA particles. Smoke particles from the burning of fuels and vegetation are also sources of SOA. Over the oceans, the most common aerosol particles are sulfates, but over continents they are SOA. Most organic molecules are smaller than 0.00004 inch (1 μm) in size.

While inorganic particles are removed from the atmosphere mainly by rain or snow, organic particles also react with oxidants, principally HYDROXYL, producing gaseous compounds. Experiments found that organic particles 0.0000008–0.000008 inch (0.02-0.2 μm) in size were entirely converted to gaseous compounds within six days. (This process is described in Stephanou, Euripedes G. "The decay of organic aerosols," *Nature,* 434, 31, March 3, 2005.)

The average concentration is between 2.5 million and 65.5 million particles per cubic inch (150,000–4 million per cm^3). The total mass of aerosol particles in the column of air resting on one square yard (meter) of the Earth's surface is more than 10 million times smaller than the mass of the air itself.

BACTERIA, SPORES, and other minute organisms that are blown from the ground, carried aloft by rising air currents, and can be transported long distances are often called aerial plankton.

Aerosol particles that have diameters smaller than 0.4μm, most being between 0.005μm and 0.1μm, are known as Aitken nuclei (for John Aitken, who discovered their existence; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). Over dry land there are often about 820–980 Aitken nuclei in each cubic inch of air (5 million to 6 million per liter). The largest of them act as CLOUD CONDENSATION NUCLEI. Over dry land there are often about 28,000 of them in each cubic foot of air (100,000 per liter).

A charged particle of dust or other substance that exists as an aerosol particle is called a large ION. It usually consists of an ion that has attached itself to an Aitken nucleus. Charged particles can be moved through the air by applying an electric field. Large ions experience more drag than small ions and so they move more slowly. This provides a means for counting the relative proportions of large and small ions. Usually there are far fewer large ions than small ions, but because of their greater mass the large ions may account for more of the total mass. In 1950, the German atmospheric scientist Christian Junge discovered that the distribution of atmospheric particles is such that for every halving of the diameter of the particles their number increases approximately tenfold.

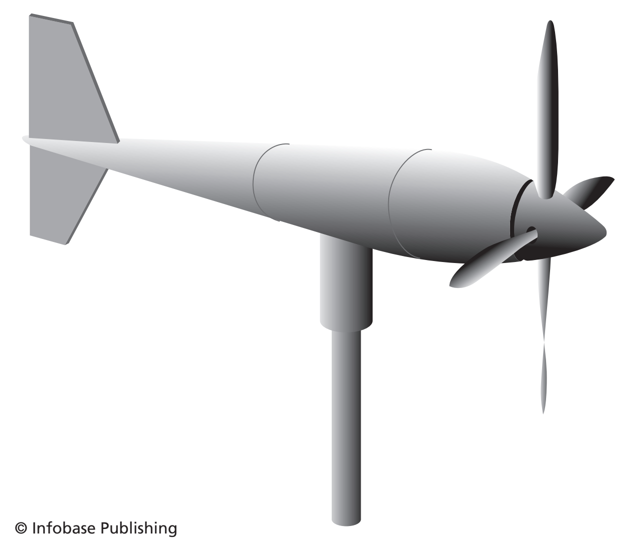
A small ion is a charged particle of dust or other substance that exists as an aerosol particle. Small ions experience less drag than large ions and so they move more rapidly. The smallest small ion particles are Aitken nuclei. The removal of small ions through their reaction with other particles is known as small-ion combination. There are two mechanisms. A small ion may adhere to a neutral Aitken nucleus. The two then form a large ion. Alternatively, a small ion may combine with a large ion of opposite charge.

Airborne POLLEN grains are also aerosol particles, and the pollination of plants by the wind is known as anemophily. Wind pollination is an unreliable method, and wind-pollinated plants produce very large amounts of pollen to increase the chance that enough pollen grains will reach female flowers to allow the plants to reproduce. Wind-pollinated plants have small flowers, usually without colored petals. People who suffer from hay fever are allergic to pollen grains and so, despite being an entirely natural aerosol constituent, pollen is often regarded as an atmospheric pollutant. All grasses are wind pollinated, but although grass pollen is the most widespread cause of hay fever, other pollen also affects sufferers (*see* AEROALLERGEN).

aerovane An instrument that measures both wind speed and WIND direction. It therefore combines the functions of a WIND VANE and an ANEMOMETER.

The aerovane has a tapering body with two large fins at the narrow end and a four-bladed propeller at the other end. It is mounted horizontally on top of a vertical column that raises it to the standard height of 33 feet (10 m) above the ground, or roof if it is mounted on the roof of a building. It is free to turn on its column.

The fins hold the propeller so it faces into the wind, thereby indicating the wind direction, and the speed at which the propeller spins indicates the wind speed. Both readings are converted into electrical impulses and are shown on dials inside the meteorological office.



The fins of an aerovane hold the propeller so it always faces into the wind. This indicates the wind direction. The rotational speed of the propeller is converted into the wind speed.

air The mixture of gases that are present naturally in the atmosphere and in which solid and liquid particles are suspended; it is the mixture of gases that all terrestrial animals breathe. In ancient times air was thought to be one of the four "elements" (the others being fire, water, and earth) from which all substances are composed. It is not an element or even a compound in the modern sense, however, but a mixture of elements and compounds the relative proportions of which have changed over long periods.

The air is a mixture of gases, which is to say that it consists of a number of gases that are thoroughly mixed together, but that remain distinct so each gas can be considered separately (*see* AIR PRESSURE: PARTIAL PRESSURE) and can be separated from the mixture. When we breathe, we inhale the complete mixture, but our lungs extract OXYGEN (O_2) from the mixture and add CARBON DIOXIDE (CO_2), the by-product of respiration, to it. We are able to do this because oxygen is present in the mixture. Oxygen is present in carbon dioxide, but it is bound in a compound, and separating it is much more difficult. The air also contains AEROSOL particles.

The proportions of the principal gases are fairly constant throughout the lower layers of the atmosphere that comprise the homosphere (*see* ATMOSPHERIC STRUCTURE). NITROGEN is the most abundant gas, followed by oxygen, but in all there are 18 gases present naturally.

The atmosphere did not always have the composition it has now. Oxygen is present as a by-product of PHOTOSYNTHESIS, for example, and nitrogen as a consequence of microbial activity. This indicates that prior to the emergence of living organisms the atmosphere consisted of a quite different gaseous mixture from the present one.

When the Earth first formed, approximately 4.5 billion (4.5×10^9) years ago, it may have had an atmosphere consisting mainly of hydrogen and helium. These gases are very common throughout the universe and were major constituents of the cloud of gas and dust out of which the solar system condensed. The gases are also very light and were soon swept away, because Earth does not exert sufficient gravitational attraction to retain them.

As this first atmosphere was lost, a second was already replacing it. This was composed of gases released from the many volcanoes on the early Earth and from the solid bodies that bombarded the Earth from space. No one knows the composition of that atmosphere, but one thing is certain: It exerted a strong GREENHOUSE EFFECT.

When the Earth first formed, the Sun radiated about 30 percent less heat than it does today. Had there been no greenhouse warming, all of the water on the surface of the Earth would have been frozen. Yet there are sedimentary rocks that have been dated to about 4 billion years old. These formed from sediments that were eroded from the land by flowing water, carried to the oceans by rivers, and deposited on the seabed. Clearly, the world was not entirely frozen.

At that time, the sky would have looked very different. The Earth was spinning faster, so days were about 14 hours long, and the Moon was much closer and would have looked very much bigger than it does now. The sky itself was probably white or perhaps pale yellow. It was certainly not blue, because that is the color of oxygen, and the air contained no more than 0.1 percent oxygen by volume.

At one time, scientists thought that carbon dioxide might have been the principal constituent of the atmosphere, with between 300 and 1,000 times more of it than there is in the present atmosphere. The carbon dioxide would have been released from volcanoes and it would have exerted a powerful greenhouse effect. It would also have reacted with iron present on the surface to form iron carbonate. Unfortunately, rocks of the appropriate age are not rich in iron carbonate. So it seems unlikely that the air was mainly carbon dioxide.

Perhaps, then, ammonia (NH_3) was the greenhouse gas? It could have formed by chemical reactions among the compounds dissolved in surface water, and it is a strong greenhouse gas. Unfortunately, ammonia breaks down in bright sunlight, so it could survive only if some other gas, such as methane (CH_4), formed a protective haze above it. By shielding the ammonia atmosphere from sunlight, however, the haze itself would have had a cooling effect that might have completely offset the greenhouse warming.

Life was present by this time. There are chemical indications of it in rocks 3.8 billion years old, and photosynthesis had begun by 2.7 billion years ago. Alongside the photosynthesizing organisms, there were others that released methane as a by-product of their metabolism. Some scientists now suspect that methane produced by living cells may have accumulated in the atmosphere and produced the necessary amount of greenhouse warming. Methane reacts with oxygen, producing carbon dioxide and water. Today a molecule of methane survives in air for only about 12 years before being oxidized, but in the oxygen-free early atmosphere it might have survived for as long as 20,000 years.

Oxygen is released as a by-product of photosynthesis. At first, gaseous oxygen reacted with volcanic gases and with iron exposed at the surface. Eventually, all the exposed iron had been oxidized, and volcanic eruptions became less frequent. Oxygen began to accumulate and between 2.2 and 1.8 billion years ago the atmospheric content of oxygen increased rapidly to 10–15 percent of its present concentration. The oxygen would have destroyed the methane, and some scientists suggest this ended the greenhouse effect, causing an ice age (*see* GLACIAL PERIOD) that covered the entire planet. A second rapid increase in the oxygen concentration, possibly linked to a decrease in the concentration of carbon dioxide, occurred about 600 million years ago and also triggered a sharp fall in temperatures.

The early atmosphere probably contained less nitrogen than the present atmosphere. The nitrogen concentration increased once life became established and the nitrogen cycle began.

Once photosynthesis was widespread and the nitrogen cycle fully functional, oxygen and nitrogen accumulated in the atmosphere and carbon dioxide was removed from it to be incorporated in living organisms and eventually to be buried in sediments that eventually became carbonate rocks. By about 500 million years ago the atmospheric gases had reached approximately their present proportions.

The table (top right) lists the constituents of the present atmosphere. Nitrogen, oxygen, and argon together comprise 99.96 percent of the air by volume, and their proportions are given as percentages of the total. Water vapor and ozone are present in such widely variable amounts that proportions cannot be given. For the minor constituents, the amounts present are given in parts per million by volume (p.p.m.v.) and for the trace constituents in parts per billion by volume (p.p.b.v.). To compare these units of measurement, 1 p.p.m. = 0.0001 percent and 1 p.p.b. = 0.0000001 percent.

Atmophile elements are the chemical elements that are concentrated in the atmosphere and that together typify its composition. These may be uncombined, for example oxygen (O_2) and nitrogen (N_2), or combined, for example carbon and oxygen in carbon dioxide (CO_2), hydrogen and oxygen in water vapor (H_2O), and carbon and hydrogen in methane (CH_4).

Composition of the present atmosphere

Gas	Chemical formula	Abundance
Major constituents		
nitrogen	N_2	78.08%
oxygen	O_2	20.95%
argon	Ar	0.93%
water vapor	H_2O	variable
Minor constituents		
carbon dioxide	CO_2	365 p.p.m.v.
neon	Ne	18 p.p.m.v.
helium	He	5 p.p.m.v.
methane	CH_4	2 p.p.m.v.
krypton	Kr	1 p.p.m.v.
hydrogen	H_2	0.5 p.p.m.v.
nitrous oxide	N_2O	0.3 p.p.m.v.
carbon monoxide	CO	0.05–0.2 p.p.m.v.
xenon	Xe	0.08 p.p.m.v.
ozone	O_3	variable
Trace constituents		
ammonia	NH_3	4 p.p.b.v.
nitrogen dioxide	NO_2	1 p.p.b.v.
sulfur dioxide	SO_2	1 p.p.b.v.
hydrogen sulfide	H_2S	0.05 p.p.b.v.

A constant gas is a constituent atmospheric gas that is present in the same proportion by volume to an altitude of about 50 miles (80 km). The most abundant constant gases are nitrogen (78.1 percent), oxygen (20.9 percent), and argon (0.9 percent). The atmosphere also contains variable gases.

A variable gas is an atmospheric constituent gas, the amount of which varies from place to place or time to time as a proportion of the whole. Water vapor, carbon dioxide, and ozone are the most important variable gases. The proportion of water vapor ranges from almost 0 percent to about 4 percent by volume. The amount of carbon dioxide varies during the day and also seasonally, in inverse proportion to the rate of plant photosynthesis. It also increases as a result of the burning of fossil fuels (*see* CARBON CYCLE). The amount of ozone present in the air also varies. The gas enters the lower atmosphere as a pollutant and is formed in the stratosphere by the action of ultraviolet radiation, so the concentration increases to a maximum of about 10 parts per million by volume in the OZONE LAYER.

Although particles suspended in the air do not constitute a gas, they behave like one and their concentration varies from place to place, and especially between air over continents and over the ocean. Consequently, aerosols are often treated as a variable gas.

Further Reading

Lovelock, James. *The Ages of Gaia.* New York: Oxford University Press, 1989.

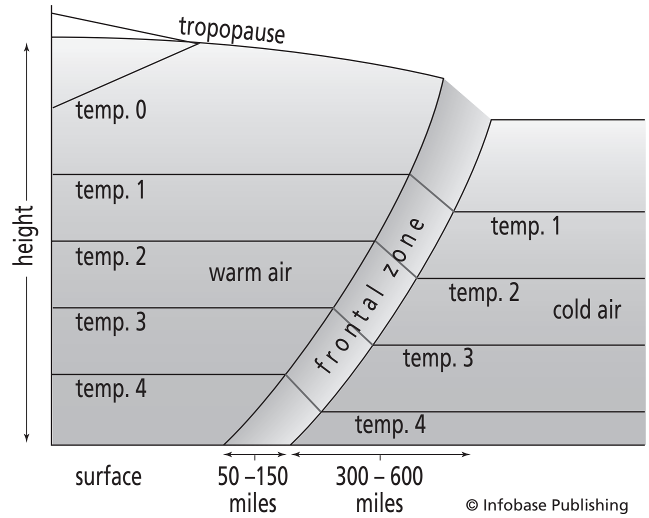
Volk, Tyler. *Gaia's Body: Toward a Physiology of Earth.* New York: Springer-Verlag, 1998.

aircraft electrification The accumulation of an electric charge on the surface of an aircraft, or the separation of a surface electric charge into charges of opposite sign on different parts of the aircraft.

air mass A body of air that covers a very large area of the Earth's surface and throughout which the physical characteristics of TEMPERATURE, HUMIDITY, and LAPSE RATE are approximately constant at every height. The constant-pressure surfaces at any height correspond to the isosteric surfaces (*see* DENSITY), and in a vertical section through the air mass the isobars and isotherms (*see* ISO-) are parallel at every height. Typically, an air mass covers a substantial part of a continent or ocean and extends from the surface to the tropopause (*see* ATMOSPHERIC STRUCTURE).

During the First World War, Vilhelm Bjerknes (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) and his colleagues at the BERGEN GEOPHYSICAL INSTITUTE studied meteorological data that were sent to them by observers located all over Scandinavia. When they plotted the distribution of temperature and humidity on maps, the pattern that emerged showed that these atmospheric characteristics remained constant over large areas. They coined the terms *air mass* to describe such homogenous bodies of air and *front* to describe the boundary between one air mass and another.

Types of air masses are classified according to the source regions in which they originate. The first division separates air masses into two types: continental air and maritime air. These are designated by the letters c and m, respectively. Air masses are further classified as arctic air (A), polar air (P), tropical air (T), and equatorial air (E). These are then combined to produce the seven types of air mass:

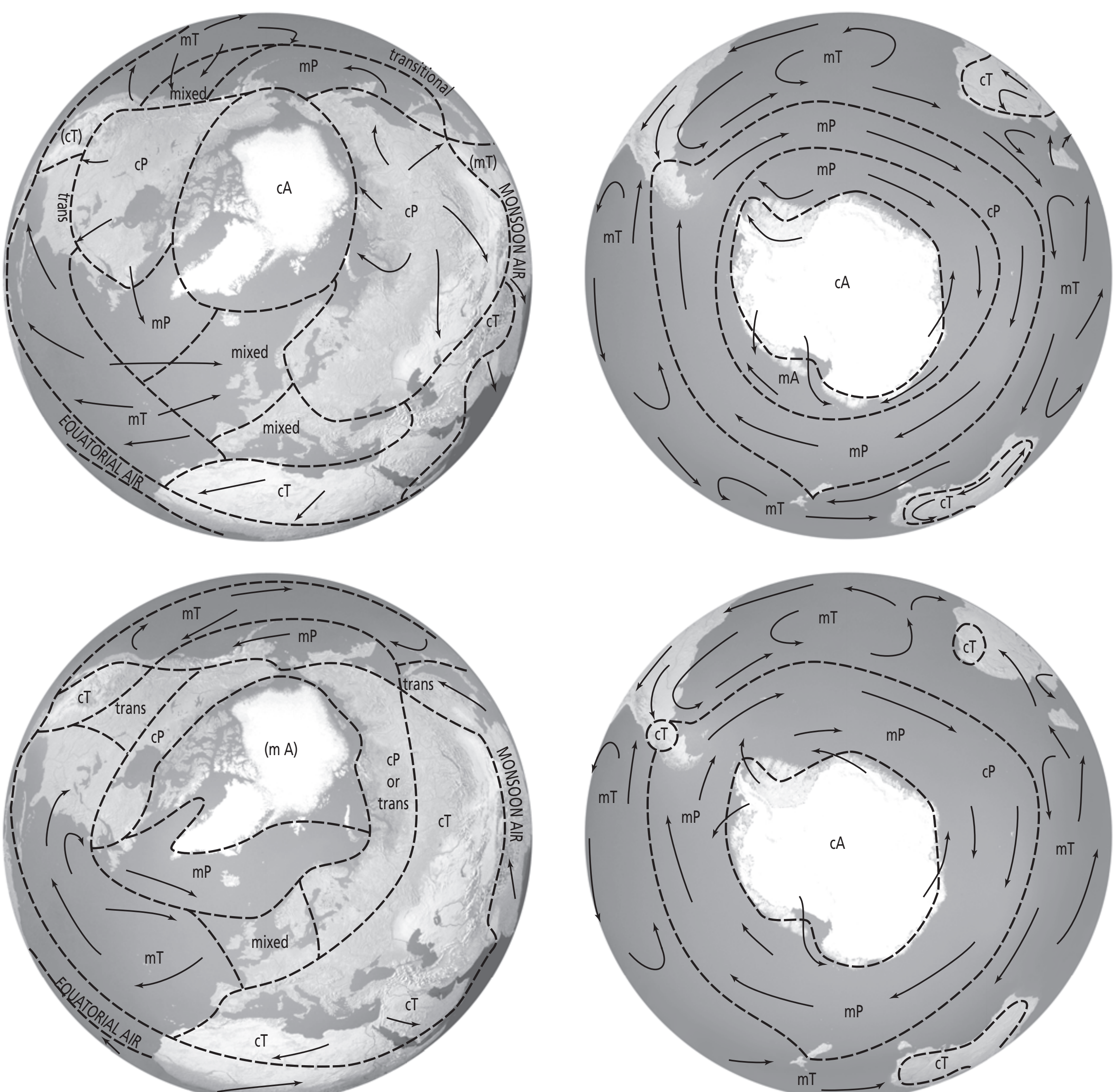


Two air masses, one warm and the other cold, are separated by a frontal zone. Throughout each air mass the temperature, humidity, and density of the air are constant at each height.

continental arctic (cA)
continental polar (cP)
continental tropical (cT)
maritime tropical (mT)
maritime polar (mP)
maritime arctic (mA)
maritime equatorial (mE)

Combining the basic types can also produce continental equatorial air. This is not included, however, because most of the equatorial region is covered by ocean, and continental equatorial air never occurs. Monsoon air is sometimes indicated separately, but its characteristics are no different from those of mT air.

Additional letters are sometimes used to designate secondary air masses. These indicate that the air is colder (k) or warmer (w) than the surface over which it is passing. If mT air crosses a continent in winter, for example, it is likely to be warmer than the surface, so it might be designated mTw. In summer, when the continental surface heats strongly, the mT air would



The four maps show the principal source regions for air masses in the Northern and Southern Hemisphere in winter and in summer. The arrows indicate the directions of the prevailing winds, and the letters identify the types of air mass (m = maritime; c = continental; A = arctic; P = polar; T = tropical).

be mTk. The designation k suggests air that produces gusty winds that quickly clear away air pollutants to bring clear, clean air. The designation w suggests very stable air, often with inversions that trap pollutants.

Air masses of the cA, cP, mP, cT, and mT types are responsible for North American weather. A narrow, tonguelike extension from a cold air mass in the direction of the equator is called a cold tongue.

A three-front model of the distribution of air masses over North America is used to analyze the BAROCLINIC structure of DEPRESSIONS from synoptic charts (*see* WEATHER MAP) and cross sections of the atmosphere. The model includes the Arctic FRONT, polar front, and between them a third front that develops at the boundary between maritime Arctic (mA) and maritime polar (mP) air or between cold and warm mP air (mPk and mPw). The three fronts mark the boundaries of four air masses: mA, mP, continental tropical (cT), and maritime tropical (mT). The fronts are approximately parallel and run from northwest to southeast.

Air masses move, driven by the prevailing winds. In middle latitudes they travel from west to east. They are so large that they often take several days to pass a point on the surface. During the time it takes for an air mass to pass, the weather remains more or less unchanged except for local phenomena such as showers and thunderstorms. Constant weather associated with an air mass is known as air mass weather.

As it travels, the characteristics of an air mass are modified by its contact with the surface beneath it. The distance over which air moves across the surface of the sea or ocean is called the fetch. A long fetch modifies the characteristics of an air mass that was formerly over a continent by moderating its temperature and increasing the amount of water vapor it carries. Together with its speed and duration, the fetch of a wind determines the height of waves (*see* WAVE CHARACTERISTICS).

Dry air will accumulate moisture as it crosses an ocean; moist air will lose moisture as it crosses a continent; and the temperature of the air will change as it crosses an extensive surface that is warmer or cooler. In this way one type of air mass is gradually transformed into another type, with quite different characteristics. Air masses form in particular areas, called source regions, and they change by moving from one source region to another.

A source region must cover an extensive area within which the surface is fairly uniform and where PRESSURE SYSTEMS are stationary for most of the time. This allows the air at any height to reach a constant temperature, pressure, and humidity, making the air mass homogeneous. The necessary conditions for the development of an air mass occur where the pressure is high and air slowly flows outward from it. Divergence (*see* STREAMLINE) prevents outside air from entering.

Northern Hemisphere air mass source regions are found over the Arctic, North America, the North Atlantic Ocean, Eurasia, and the North Pacific Ocean. Source regions in the Southern Hemisphere lie over the South Atlantic Ocean, South Pacific Ocean, Australia, and Antarctica. The air masses that originate in the source regions are classified according to their temperature and the surface over which they develop.

The geographic area that is associated with a particular source of air is known as an air shed. The concept is analogous to that of a watershed and is used in estimating the likelihood that the area will be exposed to AIR POLLUTION from elsewhere.

The changes that take place in the characteristics of an air mass as it moves away from its source region are known as air mass modification. For example, continental air, which is very dry, gathers moisture as it crosses the ocean, gradually becoming modified until it is maritime air. Air masses are modified by being heated or cooled by their passage over warmer or cooler surfaces. Heating from below tends to make the air unstable; cooling from below tends to make it more stable. EVAPORATION of water into the air and of PRECIPITATION falling through an air mass from an air mass of a different type located above it on the upper side of a frontal slope (*see* FRONT) will absorb LATENT HEAT, which will alter the lapse rate. The convergence (*see* STREAMLINE) of AIRSTREAMS and OROGRAPHIC lifting also modify the characteristics of air.

An air mass that has been slightly modified as it passes over a surface that is different from the surface over which it developed its characteristics is called a secondary air mass. For example, in winter, continental polar (cP) air moves outward from Canada and over the North Atlantic. When the cP air passes over the warm water of the North Atlantic Drift (*see* APPENDIX VI: OCEAN CURRENTS) its lower layers become warmer and unstable and their moisture content increases sharply due to evaporation. The resulting convective instability makes the air turbulent. By the time it reaches the eastern Atlantic the cP air has changed into cool maritime polar (mP) air.

The forced ascent of an air mass that occurs as it crosses high ground or is undercut by denser air at a front is known as lifting. Lifting also occurs where airstreams converge. As the air rises, its water vapor condenses, leaving the air drier.

Antarctic air comprises air masses inside the Antarctic Circle of arctic air and polar air. The continent of Antarctica, including the Antarctic Peninsula, is covered by continental arctic air (cA) in both winter and summer. In winter there is maritime polar air (mP) over the Southern Ocean adjacent to the South Atlantic (between South America and Africa) and Indian Oceans, and maritime arctic air (mA) over the Ross Sea, opposite the Pacific Ocean. In summer, mP air covers the whole of the Southern Ocean.

Arctic air is very cold and dry. The air mass originates in the high-pressure areas of the Arctic and over Antarctica. In winter, when the Arctic Ocean is completely covered by ice, continental arctic (cA) air forms over both the Arctic and over the continent of Antarctica. Maritime arctic (mA) air forms off the coast of Antarctica. In summer, mA air forms over the Arctic, but the mA disappears from the Antarctic, where there is only cA air. Differences between cA and continental polar (cP) air are most noticeable in the middle and upper troposphere, where cA air is the colder. In North America, cA air that forms in winter over the Arctic Basin and the GREENLAND ICE SHEET can bring cold waves characterized by extremely, cold, dry, and very stable air.

Continental air is very dry and forms air masses over all the continents. Continental air is hot in summer and cold in winter, except over the Arctic and Antarctica, where it is cold at all times of year.

Equatorial air is warm and humid. It forms an air mass covering the equatorial belt in both hemispheres. The air is rising on the equatorward side of the Hadley cells (*see* GENERAL CIRCULATION) and consequently equatorial air is usually cooler than tropical air. Most of the equatorial region is covered by ocean, so the air mass over it is classified as maritime equatorial (mE) and continental equatorial air does not occur.

Maritime air forms air masses over all of the oceans. Maritime air is moist, and its temperature is less extreme than that of continental air forming in the same latitude.

Pacific air is maritime air that has crossed the Rocky Mountains and has been modified by its passage over the mountains. When it reached the coast, the air was cool and moist. OROGRAPHIC lifting caused much of its water vapor to condense and fall as precipitation, and during its descent on the eastern side of the Rockies the air warms ADIABATICALLY. What was originally cool, moist air has then become warm, dry air.

Polar air is cold air that originates in the high-pressure regions of Siberia, northern Canada, and the Southern Ocean. In winter, a continental polar (cP) air mass covers all of Eurasia to the north of the Himalayas, with the exception of western Europe and North America from the far north of Canada (where cP air gives way to continental arctic air) to the south of the Great Lakes. The air is stable and brings cold waves. As it passes over the lakes, it is modified to cPk air, producing LAKE-EFFECT snow. There is no cP air mass over the Antarctic in winter or in summer. Maritime polar (mP) air forms in both winter and summer over the North Atlantic and North Pacific Oceans and over the northern part (to the north of the mA air) of the Southern Ocean. In North America, mP air from the North Pacific brings mild, humid conditions at all times of year, often with showers in winter. The air is more stable in summer and produces low stratus cloud (*see* CLOUD TYPES) and FOG near coasts.

Tropical air is warm and originates either over oceans in the subtropical high-pressure belt (*see* SUBTROPICAL HIGH), over continents at the edge of these high-pressure areas, or in the interior of continents in summer, when subsiding air produces high surface pressure and tropical air masses. In summer, continental tropical (cT) air forms in the Northern Hemisphere over the Sahara, southern Europe, and Asia between about latitude 50°N and the Himalayas, and over the southwestern United States and Mexico. It brings hot, dry weather to the U.S. The air is unstable, but so dry that it generates little cloud and it can bring DROUGHT. In the Southern Hemisphere, cT air develops over southern Argentina, southern Africa, and much of the interior of Australia. In winter, cT air forms over a rather larger area of the southwestern United States and Mexico. In Eurasia, it is pushed farther to the south, with its northern boundary at about latitude 40°N. It disappears from South America, but covers a larger area in both southern Africa and Australia. Maritime tropical (mT) air forms in winter over all the oceans between the equator and about latitude 40°N and S in both hemispheres. In summer, it extends farther north, to about 55°N. Maritime tropical air is very warm, its temperature being increased adiabatically in the subsiding air. It is also very humid and stable.

air pollution The release into the air of gases or AEROSOLS in amounts that may cause injury to living organisms. Certain pollutants can harm humans.

Pollution is not a new phenomenon. In the Middle Ages, London air was so badly polluted by SMOKE from coal fires that in 1273 Edward I passed a law banning coal burning in an attempt to curb smoke emissions. In 1306 a Londoner was tried and executed for breaking this law. Despite this, pollution was not checked, and on one occasion in 1578 Elizabeth I refused to enter London because there was so much smoke in the air. Smoke killed vegetation, ruined clothes, and the acid in it corroded buildings.

Coal burning remained the most serious source of pollution until modern times. It caused the Meuse Valley incident in 1930, severe pollution episode at Donora, Pennsylvania, in 1948, and the London smog incidents a few years later. These led to the introduction of legislation in many countries to reduce SMOKE emissions. (*See* AIR POLLUTION INCIDENTS.)

Certain products of combustion increase the acidity of precipitation and some acids can be deposited on surfaces directly, from dry air (*see* ACID DEPOSITION). This causes the type of pollution known as acid rain, which was first reported in 1852. The burning of those types of coal and oil that contain sulfur is discouraged in order to reduce the problems caused by acid deposition and acid rain.

Photochemical smog occurs naturally in some rural areas, but it becomes a pollution problem where traffic fumes become trapped by an INVERSION and the sunlight is very intense. OZONE is one product of the chemical reactions among exhaust emissions that are driven by strong sunlight. It causes severe respiratory irritation in quite small concentrations. Where fuel is not completely burned, the oxidation of carbon remains incomplete and CARBON MONOXIDE is released. This is poisonous at high doses. Lead pollution, caused by the addition of tetraethyl lead to gasoline, is now decreasing as the use of lead in fuel is phased out.

At present, pollution from vehicle emissions can be dealt with only by improving the efficiency with which vehicle engines burn fuel and by reducing traffic density at critical times. A more effective remedy for the longer term will be the widespread introduction of new types of vehicle propulsion systems that do not burn gasoline or diesel. Diesel engines also emit very fine particulate matter that is believed to cause damage to lung tissue.

Other pollutants are not directly poisonous to any living organism and until recently were not considered to be pollutants at all. Their effects are subtle.

CARBON DIOXIDE is produced whenever a carbon-based fuel is burned, because combustion is the oxidation of carbon to carbon dioxide with the release of heat energy. Carbon dioxide is a natural constituent of the atmosphere, but its increasing concentration, which is believed to be due to the burning of fossil fuels, is suspected of causing GLOBAL WARMING. Methane, released when bacteria break down organic material, is also harmless in itself, but implicated in undesired change as a greenhouse gas (*see* GREENHOUSE EFFECT).

CFCs were introduced because they are so chemically inert that they are completely nontoxic (you can safely drink them and even inhale some of them) and nonflammable. Then it was found that they are broken down in the stratosphere (*see* ATMOSPHERIC STRUCTURE) by the action of sunlight, releasing chlorine that depletes the ozone in the OZONE LAYER.

Our understanding of air pollution has increased rapidly as scientists have learned more about the chemistry of the atmosphere. At the same time, steps have been taken in many countries to reduce pollution. The air over the industrial cities of North America and the European Union is much cleaner now than it was half a century ago. Today the task facing the global community is to promote and encourage the economic and industrial development of the less-developed countries without reducing the quality of the air their people breathe.

A primary pollutant is a substance that is released into the environment, where it causes immediate pollution. The most widespread and serious primary pollutants are particulate matter, SULFUR DIOXIDE, NITROGEN OXIDES (NO_x), and unburned hydrocarbons. NO_x are both primary and secondary pollutants, because as well as being released in vehicle exhausts and from certain industrial processes, they are formed by chemical reactions that take place in the air and involve peroxyacetyl nitrates. CFCs are also considered primary pollutants, because of their role in depleting the OZONE LAYER and their global warming potential (*see* GREENHOUSE EFFECT), as are halons (*see* OZONE LAYER) and the other greenhouse gases.

A secondary pollutant is a polluting substance that is produced in the atmosphere by chemical reactions between primary pollutants. A mixture of FOG and smoke constitutes SMOG. Smoke is a primary pollutant, and the resulting smog is the secondary pollutant. Unburned hydrocarbons, which are primary pollutants released mainly in vehicle exhausts, can be oxidized in a series of steps to form peroxyacetyl nitrates. These secondary pollutants may then contribute to the formation of photochemical smog, a mixture that contains OZONE and nitrogen oxides, both of which are pollutants.

The removal of solid particles from the air when they collide with surfaces and adhere to them is called impaction. Dust and smoke particles are deposited on such surfaces as leaves, buildings, and the ground. Particles are also removed from the air by FALLOUT, rainout, and washout. The receipt of a substance, such as an atmospheric pollutant, from a distant source is called immission. It is the opposite of emission.

The dilution of pollutants as they mix with a much larger volume of air is called atmospheric dispersion. The rate of dispersion varies according to local atmospheric conditions. Pollution incidents occur when atmospheric dispersion fails to reduce pollutant concentrations to levels that are harmless. Atmospheric dispersion should not be confused with the dispersion of light (*see* SOLAR SPECTRUM).

Ventilation is the removal of pollutants from the air by the action of the wind, which introduces clean air. If air is trapped beneath an inversion and the pollutants being emitted into it are mixed thoroughly into the air beneath the inversion, then when a wind blows unpolluted air into the trapped air, the concentration of pollutants will decrease from the boundary where the wind enters, at a rate that is proportional to the wind speed. The extent to which the wind removes pollutants is known as the ventilation factor, and it is the product of the wind speed and the depth of the polluted air.

Flue gases are the cause of most industrial air pollution. A flue gas is any gas that is produced by a COMBUSTION process and that travels through a flue (*see* POLLUTION CONTROL).

Flue gases may carry fly ash, comprising very fine particles of ash that are produced by combustion. Fly ash may contain unburned hydrocarbons and other pollutants, and it may be acidic and contribute to acid deposition. The inhalation of small particles can cause damage to the lungs and respiratory passages.

Fume is a mass of solid particles, less than 0.00004 inch (1 μm) in diameter, that are suspended in the air and that result from the CONDENSATION of vapors, DEPOSITION, or chemical reactions. Fumes often contain metals or metallic compounds that may be harmful to health and inhalation of the particles themselves may cause respiratory ailments.

Pollutants can continue to cause harm after they have fallen to the ground. Fluorosis is a disease affecting ruminant animals, such as cattle and sheep, which consume excessive amounts of fluorine compounds. These excesses may occur naturally, but they can also result from industrial air pollution. Fluorosis causes weakening and mottling of the teeth and thickening of the bones. The animals usually ingest the fluorine compounds from grass onto which these air pollutants have settled.

Lead pollution is the injection of lead into the air, primarily in emissions from motor vehicles running on gasoline that contains tetraethyl lead. This compound is added to raise the octane number of the gasoline. High-octane fuel is less likely to ignite prematurely in the cylinder (this is called knocking), causing a loss in engine power and eventual damage to the engine. Lead is highly toxic in large doses, and in small doses it is believed to harm the developing nervous system of young children. Lead also damages the catalytic converters that are fitted to cars to reduce the emission of other pollutants, especially carbon monoxide and nitrogen oxides. The sale of gasoline containing tetraethyl lead is now forbidden in many countries, including the United States and the European Union.

Particulate matter, comprising the fine particles that are suspended in the atmosphere, is also a cause of considerable concern. Some particulate matter enters the atmosphere as a consequence of natural events, such as volcanic eruptions, desert winds, and forest and grass fires ignited by LIGHTNING. POLLEN grains and the SPORES of fungi and bacteria also form part of the atmospheric particulate matter. Other particles result from human activities, especially plowing dry soil, deliberate fires, and as soot from the burning of coal and oil. Collectively, atmospheric particles are known as aerosols.

Small particles can be harmful to health when they are inhaled, because they are able to penetrate deep into the lungs. Particles that are less than 25 μm in diameter, known as PM25, are believed to cause a number of respiratory illnesses and even smaller particles, 10 μm in size (PM10), are also suspected of causing harm that may be even more serious.

Soot consists of solid particles, composed mainly of carbon, which are emitted when a carbon-based fuel is burned in such a way that not all of the hydrocarbons are fully oxidized. Exhaust emissions from poorly maintained diesel engines are a major source of soot in urban areas. Soot particles are black, but dispersed among water droplets and gases they give smoke its gray color. They vary greatly in size, from less than 1 µm to 3 mm (0.12 inch). Most remain airborne for a matter of hours or at most one or two days before they are washed to the ground by rain or snow. If inhaled, however, soot particles smaller than 25 µm in size, and possibly those smaller than 10 µm, are harmful to health.

Peroxyacetyl nitrate (PAN) is a chemical compound ($CH_3CO.O_2NO_2$) that forms by a complicated series of reactions involving the oxidation of hydrocarbons, especially the unburned hydrocarbons in vehicle exhausts. PAN is fairly stable in the cold air of the upper troposphere (*see* ATMOSPHERIC STRUCTURE), but in warm air it decomposes to release nitrogen dioxide (NO_2) and the highly reactive peroxyacetyl radical $CH_3CO.O_2$. This process contributes to the atmospheric content of nitrogen oxides (NO_x), which are implicated in the formation of PHOTOCHEMICAL SMOG and ACID DEPOSITION.

PAN decomposes and re-forms by a reversible reaction, depending on the air temperature:

$$C\ H_3CO.O_2NO_2 \leftrightarrow CH_3CO.O_2 + NO_2$$

PAN is constantly forming, decomposing, and re-forming, but in warm air the reaction favors the release of NO_2 and peroxyacetyl radical. Some of the PAN survives to be carried aloft by CONVECTION currents, however, and in colder air the same reaction favors the PAN. Consequently, this essentially urban pollutant can be dispersed over a wide area.

The extent to which air is polluted determines the air quality. If the concentration of pollutants is low, air quality is said to be high. Pollution levels may be judged aesthetically, for example by a bad smell made by a substance that is otherwise harmless, but more commonly they are related to the known damage they cause to human health, vegetation, or material structures such as buildings. The concept is not absolute, because pollution levels can change according to such factors as the wind direction, time of year, and the length of time during which a pollutant is released into the air.

Sulfur dioxide is the product of the oxidation of sulfur. Sulfur dioxide (SO_2) is released into the atmosphere by the natural oxidation of reduced compounds such as hydrogen sulfide (H_2S) and dimethyl sulfide ($(CH_3)_2S$) that are emitted by living organisms. These natural processes maintain a background atmospheric concentration of about 0.0001 parts per million of SO_2. SO_2 is also released through the burning of fuels (*see* SULFUR CYCLE) and the smelting of metal ores that contain sulfur. It is also emitted by pulp and paper mills. When the atmospheric concentration of SO_2 rises significantly above the background level, the gas becomes extremely irritating and causes damage to respiratory and other plant and animal tissues.

Once it is airborne, SO_2 continues to oxidize, often to sulfur trioxide (SO_3). In the presence of catalysts this reacts with water droplets to form sulfuric acid ($SO_3 + H_2O \rightarrow H_2SO_4$). This reaction increases the acidity of CLOUD DROPLETS, fog, and mist and contributes to the problems associated with acid deposition.

SO_2 also reacts with other substances to form sulfate (SO_4) particles. These reflect sunlight and can be carried for long distances. Sulfate particles are less than 1 µm (0.00004 inch) across and act as CLOUD CONDENSATION NUCLEI. They therefore increase cloud formation, but the resulting clouds are composed of cloud droplets that are so small they fall very slowly, so PRECIPITATION can be reduced.

Transfrontier pollution is the movement of pollutants that are carried in air or water across an international frontier. Transfrontier pollution cannot be regulated and reduced by the country that suffers it acting alone, but only by addressing the source of the pollutants through international agreement. Several such agreements have been reached. For example, emissions of sulfur dioxide, especially from power-generating plants that burn coal and oil, have been reduced in order to reduce the damage to forests and fresh water that is caused by acid deposition. Acid rain damage was first reported from Sweden and was attributed to emissions from Britain, Germany, and other European countries.

The ambient air standard is a standard for the air quality in a particular place that is defined in terms of pollution levels. Industries operating in or close to such an area are required by the Air Quality Act 1967 (*see* APPENDIX IV: LAWS, REGULATIONS, AND INTERNATIONAL AGREEMENTS) to limit their emissions to levels that will not reduce the air quality to below the standard that has been set by the federal authorities.

The Pollution Standards Index (PSI) is an internationally agreed scale that provides a measure of the air quality at a particular place. The PSI compares the national air-quality standard with the amount present in the air of the pollutant that occurs at the highest concentration. If that amount is equal to what is specified in the national standard, the air is given a PSI value of 100. If the amount is less than the national standard, the air has a PSI value of less than 100, and its quality is considered to be moderate or good. If the amount is greater than the national standard, the PSI value is more than 100, and the air quality is poor. It is then graded from unhealthy to hazardous. A value of 200 is considered "very unhealthy," above 300 is "hazardous," and above 400 is "very hazardous." During the forest fires that swept Indonesia in 1997–98, the *Borneo Bulletin* reported that on April 12 the PSI reached 500.

Further Reading

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air pollution incidents Air quality varies and most industrial cities suffer episodes of poor air quality from time to time. Such pollution incidents are common. Against this background of fairly low-level pollution, occasionally there is an incident of pollution on a scale so large as to be of international concern. Some of these, including the London smogs and the pollution at Seveso, led to legislation aimed at preventing their recurrence. A few of the most serious pollution episodes of modern times are described below.

Bhopal is a city in Madhya Pradesh, in central India, where one of the most serious industrial accidents in history occurred on December 3, 1984. It polluted the air and caused the deaths of about 2,000 people immediately and injuries to about 300,000. An estimated 8,000 people died later, bringing the final death toll to about 10,000, although some organizations have estimated there were up to 16,000 deaths. Young children and the elderly were especially susceptible.

The accident occurred in the early morning, while most people were asleep, at a pesticide factory owned by the Indian subsidiary of Union Carbide Corporation. A series of mechanical failures and human errors caused a cloud of about 49.5 tons (45 tonnes) of methyl isocyanate to be released into the air. Being heavier than air, the poisonous gas settled close to ground level and moved through the buildings nearby. The local authorities had no information about the toxic material being held inside the factory and no plans for dealing with an emergency. It was an hour before the alarm was raised, by which time many people were already dead or fatally ill. There was then a panic and more people were injured as they tried to escape from the area, many suffering from eye and respiratory irritation caused by the poison.

Chernobyl is the Ukrainian site of a nuclear power plant comprising four reactors of the RMBK–1000 type, designed in the 1960s, which uses a graphite moderator and water as a coolant. On April 25, 1986, the Number Four reactor was being shut down for routine maintenance and the operators sought to take advantage of the shutdown to test the safety equipment. One test aimed to determine how long the plant's turbogenerator would continue supplying enough power to keep the plant operating safely once the steam supply to the turbines was cut off. This necessitated turning off the reactor's emergency cooling system to prevent it from cutting in automatically during the test (a procedure strictly forbidden by the authorities).

At about 1:20 A.M. (local time) on the morning of April 26, with the reactor running at 6 percent of full power, the operators withdrew all 211 control rods (which was also strictly forbidden). The head of the shift realized the danger 40 seconds later and ordered the control rods to be lowered, but for technical reasons this exacerbated the problem and there was a positive scram. Within one second the power surged to several hundred times its normal operating output and cans containing the reactor fuel burst open, causing an explosion.

Water then came into contact with the hot fuel and reacted with the graphite to form water gas—a highly explosive mixture of hydrogen and carbon. This exploded, blowing the top off the reactor and releasing a cloud of radioactive material that contaminated a large area downwind of Chernobyl, in Ukraine, Belarus, and the Russian Federation.

Approximately 50 reactor and emergency workers died soon after the accident from acute radiation syndrome. Of the people in the surrounding area who ate food contaminated with radioactive iodine shortly after the accident, about 4,000 developed thyroid cancer. Most of the victims were children and adolescents and nine died; the recovery rate from this type of cancer is almost 99 percent.

A study by the Chernobyl Forum, comprising representatives from the World Health Organization, International Atomic Energy Agency, the United Nations Development Programme, and the governments of Ukraine, Belarus, and the Russian Federation of the consequences of the accident published its findings in September 2005. It predicted that of the 600,000 emergency workers, local residents, and evacuees who were exposed to radiation, approximately 4,000 are likely to die from cancer resulting from the accident. This is a 3 percent increase in the number of persons expected to die from cancer in a population of that size.

Donora is a town (pop. 7.500) 28 miles (45 km) to the south of Pittsburgh, Pennsylvania, where one of the most serious of all air pollution incidents took place in October 1948. For a week, FOG remained trapped beneath an INVERSION and SMOKE and fumes from a zinc works and an iron works both owned by the American Steel and Wire Company mixed with the water droplets.

On Friday, October 28, sulfur dioxide from the factories had formed a sulfuric acid mist, and by Saturday people began arriving at hospitals, complaining of breathing difficulties, headaches, nausea, and abdominal pains. That is when the first deaths occurred.

On Sunday, the town was closed to traffic, including ambulances, partly due to poor visibility. Firefighters visited homes with oxygen to help people with respiratory problems. On Sunday evening, the zinc works closed, but rain washed the acid from the air and the factory opened again on Monday. About 6,000 people—half the population at the time—were made ill and 17 died. Two more people died later from the effects of the pollution.

Every autumn, farmers and loggers in Sumatra and Kalminantan Province, and Java, all in Indonesia, set fires to burn unwanted vegetation. In September 1997, during a severe drought caused by one of the most intense El Niño episodes ever recorded, the Indonesian fires blazed out of control. They released a pall of smoke and PHOTOCHEMICAL SMOG that covered Singapore and parts of Malaysia, Brunei, and Papua New Guinea, as well as other parts of Indonesia. Thailand, Hong Kong, and the Philippines were also affected, but less severely.

On September 17 the Indonesian environment minister considered evacuating the entire population of 45,000 from the town of Rengat, Sumatra, but a change in wind direction brought an improvement in air quality. States of emergency were declared on September 19 in Kalimantan and Sarawak, Malaysia, and on September 20 visibility was so poor that two ships collided in the Malacca Strait. When the air pollution index (*see* AIR POLLUTION) reached 635 in Kuching, Sarawak, the authorities closed the airport, ordered shops and schools to close, and advised everyone to remain indoors. On September 23 the index reached 839 in Kuching. This is possibly the highest air pollution level ever recorded anywhere in the world.

The arrival of a brief rainy season in November damped down the fires, but they broke out again in January and continued until May 1998. On April 30, the authorities in Kuala Lumpur, Malaysia, hosed down the city from the roofs of skyscrapers in order to wash the smog and particulate matter from the air.

The London smog incidents were two episodes in London, England, each of which lasted for several days, during which very wet SMOG was trapped beneath a temperature inversion. The smog accumulated and thickened, causing illness and many deaths.

In the first episode, in December 1952, more than 4,000 people died in the Greater London area as a direct consequence of the smog. Seven times more people died from bronchitis and pneumonia than in the same period in previous years. The 1952 smog was extremely acid, with a pH of about 1.6, making it very corrosive. This event stimulated the government to act, and the Clean Air Act, imposing strict controls on the domestic burning of coal and wood in London and other cities, became law in 1956.

The second smog incident occurred in December 1962. About 700 people died as a direct result of that smog. The reduction compared with the 1952 death toll was attributed to the Clean Air Act, which by then was starting to take effect. Although the number of deaths in the 1952 incident was dramatic and widely publicized, most of those who died were already in very poor health, and it is doubtful whether they would have survived the winter even had there been no smog. Nor were these the first severe smog incidents. London pea soupers were well known. There are records of them in other years, and one similar to those of 1952 and 1962 lasted from December 27, 1813 to January 2, 1814.

The Meuse valley incident was an air pollution disaster that occurred between December 1 and December 5, 1930, between the towns of Seraing and Huy near

Liège in the valley of the river Meuse in southern Belgium. The affected area was about 24 km (15 miles) long and 2.4 km (1.5 miles) wide and surrounded by hills 330 feet (100 m) high. There were many factories in the area, including steel mills, power plants, lime kilns, and glassworks, as well as plants refining zinc and manufacturing sulfuric acid and fertilizer. All of them used coal-burning furnaces as a source of power and most of the local inhabitants burned coal in their homes.

Cold weather and a KATABATIC WIND flowing down from the hills combined to produce fog that was trapped, together with the polluting chimney emissions, beneath an inversion. This produced dense smog. People suffered from chest pains, shortness of breath, and coughing produced by more than 30 contaminants, sulfur compounds being the most serious. The worst affected were those with a previous history of respiratory complaints and the elderly. Several hundred people became ill and more than 60 died. Many cattle also had to be slaughtered. This was the first recorded major air pollution incident.

The Poza Rica incident was an industrial accident that happened in 1950 at Poza Rica, Mexico, and caused serious air pollution. Equipment failed at the sulfur-recovery unit of an oil refinery, leading to the release of large amounts of hydrogen sulfide (H_2S), which was trapped beneath an inversion. Hydrogen sulfide is poisonous and evil-smelling (it smells like rotten eggs). At low concentrations it causes headaches and at high concentrations it is lethal. A total of about 320 people were made ill at Poza Rica and 22 people died.

Seveso is a village near Milan, Italy, where in July 1976 an explosion released a large amount of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD), popularly known as dioxin (although it is only one of a number of related compounds, all known as dioxins). The factory was manufacturing the herbicide 2,4,5-T.

Following the incident, all 700 residents of Seveso were evacuated, more than 600 domestic animals were destroyed, and the vegetation within a 5-mile (8-km) radius was removed and incinerated. There were no human deaths, but a number of persons who had been heavily exposed suffered from chloracne, a distressing skin complaint.

Further Reading

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air pressure is the force that is exerted by the weight of overlying air. The weight of the atmosphere is the magnitude of the gravitational force that attracts the mass of the atmosphere. The entire atmosphere weighs about 5.83×10^{15} tons (5.3×10^{15} t). At sea level this exerts an average pressure of 14.7 pounds per square inch (1 kg cm^{-2} or 1 bar, see UNITS OF MEASUREMENT).

Because air pressure is caused by gravity, it acts directly downward, so at sea level a surface area of 18 square inches (116 cm^2), for example, which is approximately the area of a hand, experiences a pressure of about 265 pounds (120 kg). The hand is not crushed, partly because it is structured to withstand the pressure and partly because of the way the force is applied. Air pressure is exerted by the movement of air molecules. The more molecules there are, the greater is the pressure that they exert. You can picture them as rubber balls being thrown hard against a surface and bouncing back. Molecules move in all directions, however, so there are as many of them moving upward and sideways as there are moving downward. Consequently, the pressure applied to one side of the hand is precisely balanced by the pressure applied to the other side and to the edges. The true magnitude of air pressure can be seen when two surfaces are joined so closely that no air remains between them. It is then extremely difficult to separate them.

This was most impressively demonstrated in 1654, when the German physicist Otto von Guericke (1602–86, *see* APPENDIX I, BIOGRAPHICAL ENTRIES) sought to convince the emperor, Ferdinand III, that it is possible for a vacuum to exist (thus contradicting the popular view, derived from Aristotle, that "nature abhors a vacuum"). Von Guericke had two metal hemispheres constructed in such a way that they fitted together along a greased flange that made an airtight seal. He joined the hemispheres and evacuated the air from inside them using the air pump he had invented. Once the air had been removed from inside the device, the external air pressure forced the hemispheres together. Von Guericke then ordered two teams of horses to be attached, one to each of the hemispheres, and to attempt to pull them apart. The horses were unable to do so, despite straining with all their might. When von Guericke disconnected the pump and allowed air to return to the sphere, the two sections fell apart under their own weight. Von Guericke lived in the city of Magdeburg, which is where he conducted his demonstration. Consequently, the hemispheres are known as Magdeburg hemispheres.

Exposure to low air pressure can cause illness in persons who are not acclimatized to it. The soroche is a form of mountain sickness that afflicts persons who travel from the coast to the puna region of Peru, high in the Andes at an elevation of 10,000–15,000 feet (3,000–4,500 m), where the air pressure is about 675 mb. The soroche causes breathlessness, palpitations, loss of appetite, and sometimes nose-bleeding.

Air pressure varies with the temperature and density of the air, which are related to each other by the GAS LAWS. Air pressure decreases with height, because the distance to the top of the atmosphere decreases, and so, therefore, does the weight of overlying air.

The air pressure at the center of an ANTICYCLONE or CYCLONE at a particular time is known as the central pressure. It is the highest pressure in a region of high pressure and the lowest pressure in a region of low pressure.

Isallobaric is an adjective that describes a constant or equal change in atmospheric pressure over a spatial distance or over a specified time.

Katabaric, alternatively known as katallobaric, is an adjective that is applied to any phenomenon associated with a fall in atmospheric pressure.

In a mixture of gases, the share of the total pressure that can be attributed to any one of the constituent gases is known as the partial pressure of that gas. For example, if the atmospheric pressure is 1000 mb and oxygen accounts for 21 percent of the mass of the air, then the partial pressure for oxygen is 210 mb.

The height above sea level at which the air pressure in a standard atmosphere (*see* UNITS OF MEASUREMENT) would be the same as the pressure measured at the surface in a particular place is called the pressure altitude (*compare* DENSITY: DENSITY ALTITUDE). The use of pressure altitudes allows atmospheric pressure to be expressed in terms of altitude. For example, in summer the pressure altitude at the VOSTOK STATION in Antarctica is about 10 percent higher than the true altitude, and in winter it is about 15 percent higher. The difference between the true altitude and pressure altitude is called the pressure-altitude variation.

An area of high air pressure that is produced by the cooling of air that is in contact with a cold surface is called a thermal high. The cold air contracts and becomes denser, drawing down more air from higher in the air column and thus increasing the surface pressure.

The heating of the surface by sunshine produces a change in air pressure that follows the progress of the Sun and therefore progresses around the Earth in a similar fashion to the gravitational TIDES. This phenomenon is called a thermal tide.

airstream A large-scale movement of air across a continent or an ocean that is associated with the prevailing winds in that latitude (*see* WIND SYSTEMS).

The airstream that most influences the climate of the western coast of North America arrives from the Pacific Ocean and brings maritime polar air (*see* AIR MASS). To the east of the Rocky Mountains, the climate is dominated by airstreams bringing continental polar air and Arctic air.

albedo A measure of the reflectivity of a surface, expressed as the proportion of the radiation falling on the surface that is reflected. If all of the radiation is reflected, the surface has an albedo of 1.0, or 100 percent. Radiation that is not reflected is absorbed (*see* ABSORPTION OF RADIATION), therefore the albedo of a surface strongly influences the extent to which sunshine will penetrate to warm anything beneath the surface.

We take advantage of this property of materials. In summer we wear white or pale-colored clothes. Pale colors reflect light and white reflects most of all, so these colors help to keep us cool. In winter we wear dark colors, which absorb more of the sunshine.

Unfortunately, it is not quite so simple, because albedo varies according to the wavelength of the radiation. Materials that have a high albedo in visible light, so they appear as pale colors, may absorb quite well at infrared wavelengths (*see* SOLAR SPECTRUM). Wearing garments of such a material will do little to protect against solar warmth. Solar radiation is most intense at about 0.5 µm, which is the wavelength of green visible light. Many surfaces have a different

Comparative Albedos

Surface	Green	Infrared
Dry sand	0.23	0.30
Wet sand	0.12	0.19
Clean ice	0.54	0.32
Dirty ice	0.33	0.19

albedo at this wavelength than at an infrared wavelength of 0.8 μm.

Different surfaces have different albedo values. The table above lists several examples of albedos at green visible-light and infrared wavelengths.

Calculations of the amount of energy that a surface absorbs must take account of the variation of albedo with wavelength. Regardless of wavelength, absorbed radiation is converted to heat, but a measure of the albedo of a surface in visible light does not give a reliable value from which to calculate the warming effect of sunlight. Whether it is wet or dry, sand is more highly reflective at infrared than at shorter wavelengths, and whether it is clean or dirty, ice absorbs more strongly in infrared than in green radiation wavelengths.

The amount of radiation that is absorbed by a surface is most closely related to the albedo at short wavelengths, of less than 4 μm. When values for albedos are given, unless stated otherwise they refer to the albedo at these wavelengths.

Albedo also varies with the ANGLE OF INCIDENCE of the solar radiation. This is seen most clearly over water, such as a lake or the sea. When the Sun is high in the sky the water appears dark. In temperate latitudes in summer the noonday Sun is at an elevation of about 50° and a water surface has an albedo of about 0.025 (meaning that it reflects 97.5 percent of the sunlight falling upon it). If the Sun is directly overhead, the albedo of water is even lower, at about 0.02. When the Sun is low in the sky, at an angle of 10°, the albedo increases to 0.35 and at dawn and sunset, when the Sun is touching the horizon and the angle of incidence is close to 0°, the albedo is greater than 0.99. Although this is most obvious in the case of water, to a greater or lesser extent it applies to all surfaces and most of all to level ones. Level sand and ice surfaces also have albedos approaching 1.0 when the angle of incidence is close to 0°.

Since albedo varies with latitude, season, and time of day, the values for particular surfaces are calculated as the global average through the year. Figures for albedo values therefore represent global averages of albedo at wavelengths of less than 4 μm, which is at the short-wave end of the wavelength of violet light.

There have been fears that Earth's albedo was increasing due to a rise in the amount of particulate matter (AEROSOL) associated with AIR POLLUTION. An increase in the atmospheric albedo reduces the amount of solar radiation reaching the surface: the particles shade the surface. Studies suggested the amount of INSOLATION in Israel decreased by 50 percent during the second half of the 20th century. Globally, the decrease amounted to 1–2 percent per decade between 1950 and 1990. The phenomenon was named global dimming.

More recent research suggests that although global dimming may have occurred between 1960 and 1990, since 1990 average insolation has increased. No one can be certain of the cause, but it is possible that the dimming was due to pollution and its reversal was

Albedo

Surface	Value
Fresh snow	0.75–0.95
Old snow	0.40–0.70
Cumuliform cloud	0.70–0.90
Stratiform cloud	0.59–0.84
Cirrostratus	0.44–0.50
Sea ice	0.30–0.40
Dry sand	0.35–0.45
Wet sand	0.20–0.30
Desert	0.25–0.30
Meadow	0.10–0.20
Field crops	0.15–0.25
Deciduous forest	0.10–0.20
Coniferous forest	0.05–0.15
Concrete	0.17–0.27
Black road	0.05–0.10

linked to falling pollution from industries in the former Soviet Union as its economy contracted, combined with the antipollution measures taken in many countries.

Alberta low An area of low pressure that sometimes develops on the eastern slopes of the Rocky Mountains, in the Canadian province of Alberta. Air passing over the mountains develops a cyclonic circulation (*see* CYCLONE) and then the system moves eastward, bringing storms with heavy precipitation.

Aleutian low One of the two semipermanent areas of low pressure in the Northern Hemisphere (the other is the ICELANDIC LOW). The Aleutian low is centered over the Aleutian Islands, southwest of Alaska in the North Pacific at about 50°N, and it covers a large area.

The low is described as semipermanent because, although it forms, dissipates, and reforms, it is present for most of the winter and it moves very little. The intensity of the system varies, with the lowest pressure occurring when the atmospheric circulation is strong. Pressure is lowest in January, when it averages 1002 mb.

The Aleutian low is farther south than the Icelandic low. This is due to the presence of the Aleutian Islands, which restrict the northward movement of currents in the North Pacific Ocean, and to the Gulf Stream (*see* APPENDIX VI: OCEAN CURRENTS), which pushes the Icelandic low northward. The Aleutian low generates many storms that travel eastward along the polar front (*see* FRONT) and tend to merge.

algorithm In the atmospheric sciences, an algorithm is a set of equations that make it possible to infer one set of data, such as the concentration of OZONE in the air, from another set, such as the intensity of radiation at certain wavelengths. This allows quantities that are difficult or impossible to measure to be calculated from quantities that can be measured simply and precisely. In this example, because ozone absorbs electromagnetic radiation at particular wavelengths, measuring the intensity of radiation at those wavelengths and comparing it with the intensity at other wavelengths reveals the amount of radiation being absorbed by ozone. From this the ozone concentration can be calculated.

In computing, an algorithm is a sequence of steps that, if followed, leads to the accomplishment of a specified task. Written as an ordered series of instructions in a language or code appropriate to the computer, an algorithm becomes a program.

The word *algorithm* is derived from *al-Khwarizmi* the surname of Muhammad ibn-Musa al-Khwarizmi (*c.* 780-*c.* 850), whose book *Hisab al-jabr w'al-muqabala* ("Calculation by Restoration and Reduction"), translated into English in 1145, also gave the language the word *algebra,* from *al-jabr.*

alpha decay A type of RADIOACTIVE DECAY in which the nuclei of the decaying atoms emit alpha particles. Alpha particles consist of two protons and two neutrons and have a charge of +2. The loss of an alpha particle decreases the atomic number (the number of protons in the nucleus) by 2.

Uranium-238 (^{238}U) decays by alpha decay to thorium-234 (^{234}Th). A stream of alpha particles is known as alpha radiation. Alpha radiation is emitted naturally by elements present in the soil and rocks. Ionizing radiation (*see* ION) ionizes the air molecules with which it collides.

altimeter An instrument that measures the altitude of the person or device carrying it. There are two types, one that relates altitude to atmospheric pressure and one that measures the time taken for electromagnetic radiation to be reflected.

The pressure altimeter, which is the type most widely used in aircraft, consists of an aneroid BAROMETER located in a PITOT TUBE and linked to a dial on the instrument panel. In addition to the pointers indicating altitude in feet or meters, the dial displays sea-level barometric pressure in millibars. This can be adjusted and is set to the current value. The instrument then computes altitude by comparing the sea-level pressure with the pressure detected by its aneroid capsules. This type of altimeter usually indicates height above sea level, but can be set to the surface pressure, when it indicates the height above the surface. This is less useful, because as the instrument moves from place to place the surface elevation below it is likely to vary and the instrument reading takes no account of this and is consequently inaccurate.

A hypsometer also measures atmospheric pressure, but does so by its effects on the boiling point of a liquid. This varies inversely with air pressure, so altitude can be calculated from the TEMPERATURE at which the liquid boils. The instrument consists of a cylindrical vessel containing the liquid (which is usually water), that is surrounded by a jacket through which the vapor can circulate, and that contains a thermometer.

A radar altimeter measures altitude above the ground surface. It transmits a RADAR signal that is reflected from the surface and measures the time that elapses between the transmission of the signal and the receipt of its reflection. A laser altimeter works in the same way, but using a laser beam rather than a radio signal. The altitude (a) is calculated by the equation $a = ct/2$, where c is the speed of light and t is the time that elapses between transmission and reception.

Measuring the topography of a land surface by means of a radar altimeter carried by an aircraft or space vehicle is called radar altimetry. The altimeter measures the distance between the vehicle carrying it and the surface vertically below it. Provided the vehicle remains at a constant height in relation to a DATUM level (not the ground surface) its distance to the surface will vary according to changes in the ground elevation. With a series of passes the physical features of the landscape can be measured and plotted, and the plots used to compile a map.

Altithermal A period lasting from about 5,000 to 8,000 years ago during which the average temperature was up to about 5°F (2.8°C) warmer than that of today.

ambient Surrounding a person, object, or area. The ambient temperature is the temperature of the air surrounding the place where the measurement is made and the ambient pressure is the pressure of the surrounding air. Ambient air standards (*see* AIR POLLUTION) set quality criteria for the surrounding air. The word is derived from the Latin verb *ambire,* which means "to go around."

ammonium sulfate haze The first stage in the formation of cirrus cloud (*see* CLOUD TYPES), which occurs when the relative HUMIDITY (RH) exceeds 75–80 percent. Ammonium sulfate and sea-salt AEROSOLS are soluble in water. Liquid water condenses onto them (and will condense onto sulfuric acid aerosols at any RH). The droplets form a thin HAZE.

As the RH rises to above 100 percent, condensation accelerates and the haze droplets grow larger. When they are more than 0.00008 inch (2 μm) across, they are classed as CLOUD DROPLETS and at this stage the cloud is visible.

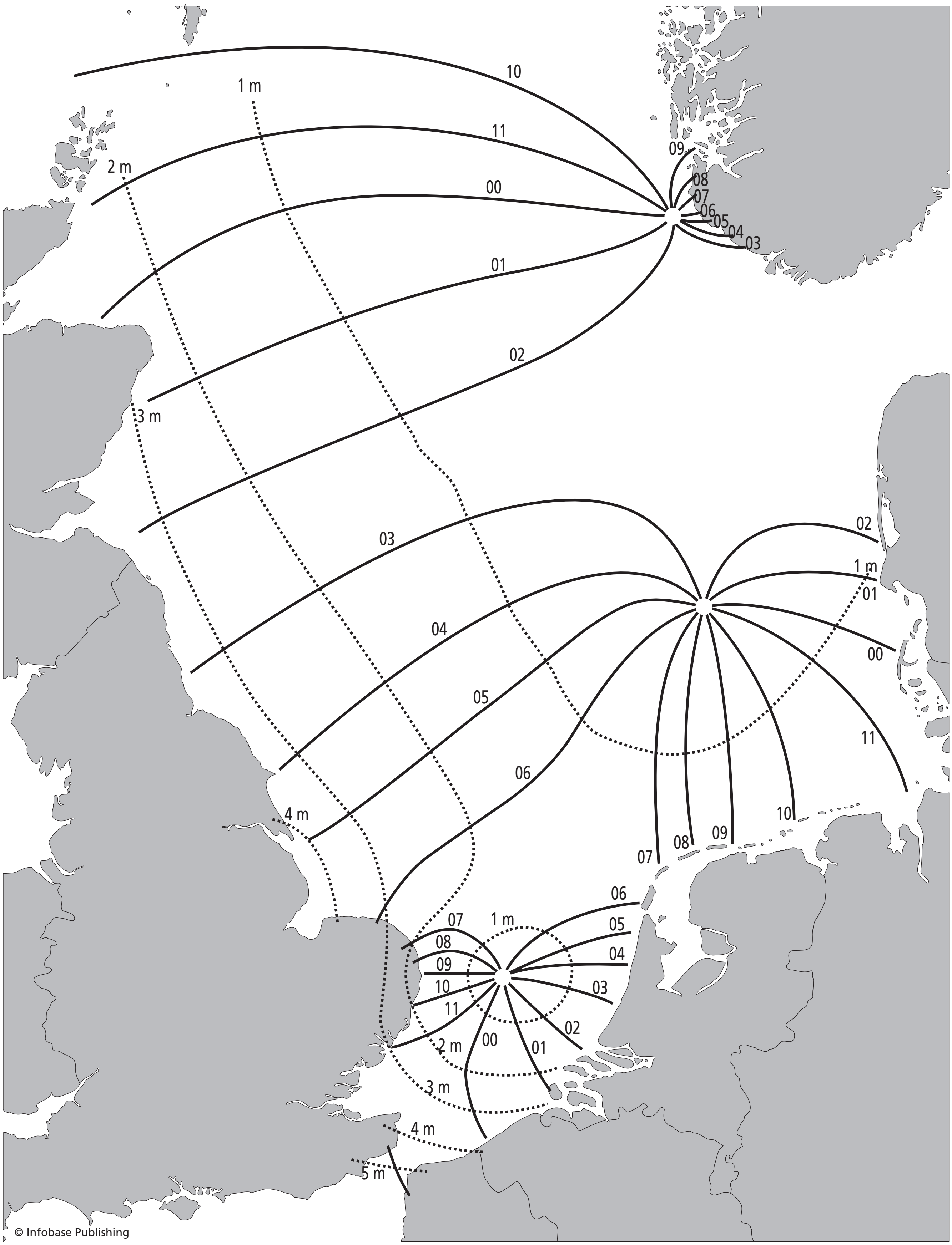
The temperature at the height where cirrus forms is below freezing and many of the supercooled (*see* SUPERCOOLING) liquid water droplets contain solid particles that act as FREEZING NUCLEI. This allows ICE CRYSTALS to grow. Ice crystals will form in the absence of freezing nuclei if the temperature is below -40°F (-40°C). The ice crystals grow rapidly until they are about 0.002 inch (50 μm) across, after which their growth slows.

amphidromic point A geographical position around which seawater circulates in the course of the tidal flow. The TIDES produce no rise or fall of water at the amphidromic points themselves. The word *amphidromic* is derived from the Amphidromia, an ancient Greek naming festival for a newly born child, at which friends carried the child around the hearth.

An amphidromic point occurs where water flows from the ocean and into a partially landlocked sea. The resulting tidal stream is affected by the CORIOLIS EFFECT (CorF), which causes it to swing, so it ends by circulating around a point. The tidal range (*see* TIDES) increases with distance from an amphidromic point.

The North Sea is a good example of a sea that has an amphidromic tidal flow. Water from the Atlantic Ocean enters the North Sea through the Straits of Dover in the south and around the north of Scotland. This produces three amphidromic points. One is midway between the bulge of eastern England and the Netherlands, the second is the eastern North Sea level with Denmark, and the third lies off southwestern Norway.

The times of high and low water follow a circle around an amphidromic point. Lines, called cotidal lines, can be drawn radiating from an amphidromic point to link the points at which high tide is reached at a particular time. Corange lines can also be drawn to link points at which the average tidal range is the same. These surround the amphidromic point, sometimes as a series of concentric circles.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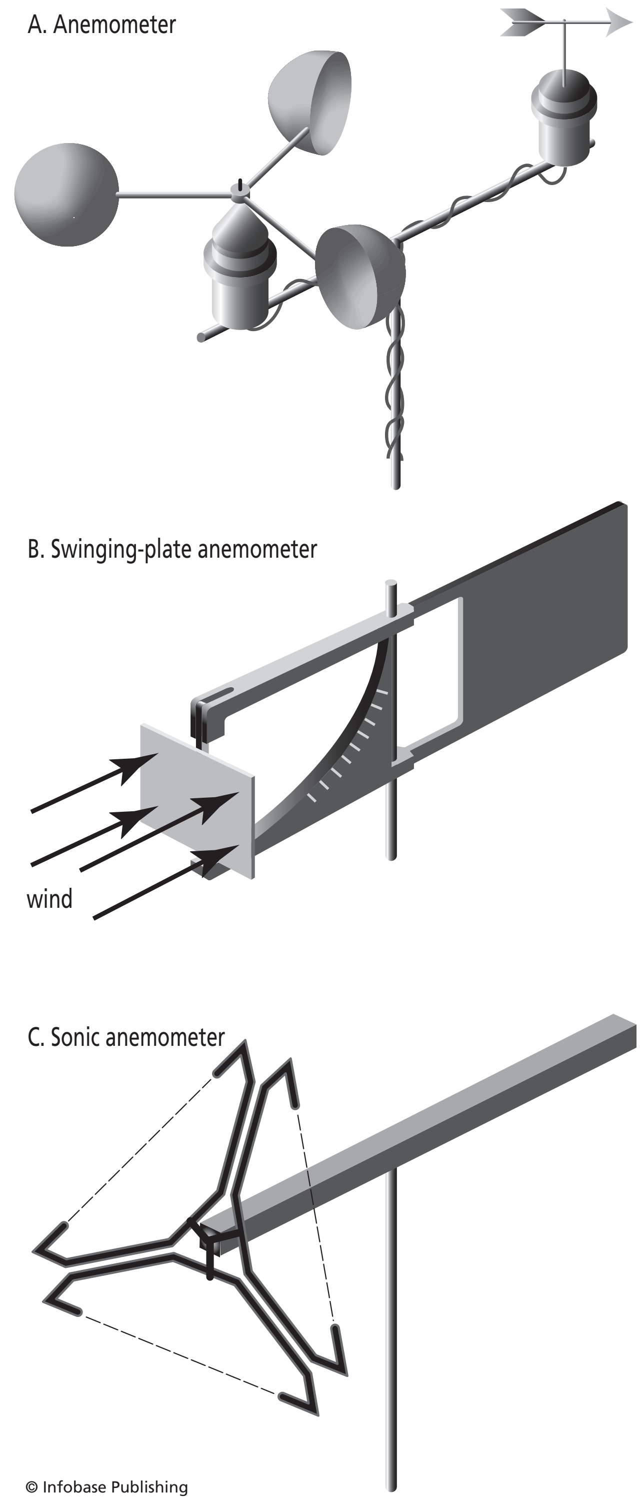
***(Opposite page)* There are three amphidromic points in the North Sea, between the eastern United Kingdom and continental Europe. The solid lines are cotidal lines. These indicate the time of high water measured is lunar hours, of approximately one hour two minutes, after the Moon has passed the Greenwich meridian. The broken lines are corange lines, indicating the average tidal range.**

anabatic wind A wind that blows up the side of a hill (*see* WIND SYSTEMS: VALLEY BREEZE). Anabatic winds occur on warm afternoons on the sides of narrow valleys, especially those that are aligned north–south, so the valley sides and floor are not shaded from the Sun.

As the ground warms, the air in contact with the surface is also warmed, and the air expands. The sides of the valley prevent the air from expanding to the sides, and therefore it expands upward, producing a gentle flow up the valley sides. At the same time, in many valleys the sides are warmed more strongly than the valley floor, so the warming of the air increases with height. This accelerates the upslope movement of air.

anemometer An instrument that is used to measure the surface WIND SPEED. It is very difficult to measure wind speed directly (*see* WIND SPEED). To do so would necessitate labeling a small volume of air and tracking its movement over a measured distance. Radiosonde WEATHER BALLOONS are used to measure the speed and direction of the upper-level wind. The balloon moves with the air surrounding it, transmitting a radio signal that is tracked from the ground.

The surface wind is measured by its effect on a physical object. The rotating cups anemometer is the device that is most widely used. It consists of three or four hemispherical or conical cups that are mounted on arms separated by 120° or 90°, depending on the number of cups, and attached to a vertical axis. The wind exerts more pressure on the concave surfaces than on the convex surfaces. This causes the cups to turn about the axis, and the rotational speed of the axis is converted into the wind speed and displayed on a panel attached below the cups or remotely, by a needle on a dial. A rotating cups anemometer tends to overestimate the speed of wind GUSTS, because the cups accelerate more quickly than they slow down.



***(This page)* The rotating cups anemometer measures the speed with which its cups spin about their vertical axis. It is often linked to a wind vane, so the combined instrument measures wind direction as well as speed. The swinging-plate anemometer measures the pressure the wind exerts on its flat plate. The sonic anemometer measures the speed of sound through moving air.**

The anemometer measures only the speed, not the direction of the wind, but it is sometimes mounted at one end of a horizontal arm, and a WIND VANE is mounted at the other end. In this design, a second needle on a dial shows the direction indicated by the wind vane.

An anemometer registers the speed of the wind at a particular moment, but it can also determine the average wind speed over a period, by measuring the run of wind.

The run of wind is the "length" of a wind. Rotating-cup anemometers spin around a vertical axis. The number of revolutions the instrument makes in a measured period of time can be converted into the horizontal distance (D) that one of the cups has traveled by:

$$D = \pi dR$$

where d is the diameter of the circle traveled by the cup and R is the number of revolutions. This can then be converted into the speed (S) by:

$$S = D/T$$

where T is the time that elapses. T can be of any length, from a few minutes to a day, and the result of the calculation is the average wind speed over that period. This is a more useful value than the wind speed measured at any particular moment, because the speed of the wind changes constantly and all instruments experience a lag in registering the changes. A typical cup anemometer experiences a lag of about 8 seconds in registering a change of speed at about 4 knots (4.6 mph, 7.4 km/h), but a smaller lag at higher speeds. About 50 feet (15 m) of air must pass the anemometer before it will give an accurate reading.

A swinging-plate anemometer, also called a pressure-plate anemometer, is better than a rotating-cups anemometer for measuring the speed of gusts. It consists of a flat plate that swings freely at one end of a horizontal arm. A wind vane is fixed to the opposite end of the arm and the arm is free to rotate about a vertical axis. The vane ensures that the plate is always oriented at right angles to the direction of the wind. Air pressure makes the plate swing inward, and the distance that it swings is converted into a wind speed that is read from a scale.

A bridled anemometer resembles a rotating-cups anemometer, but has more cups: There are commonly 32. The vertical axis is bridled, which is to say that its movement is checked by a spring. The rotation of the axis exerts tension on the spring. This is detected electronically and shown as wind speed on a dial. This type of anemometer is often used on ships.

A four-bladed propeller spins if it is held at right angles to the wind. This is a propeller anemometer or AEROVANE.

A pressure anemometer also measures the pressure exerted by the wind. It uses a PITOT TUBE that is attached to a vane; the vane ensures that it always faces directly into the wind.

A vertical anemometer measures the vertical component of wind speed. It consists of a pressure anemometer with its plate mounted horizontally rather than vertically, or of a propeller mounted on a vertical axis.

Vertical air motion high above the ground and in clouds is measured by specialized instruments carried on aircraft. The atmosphere forms horizontal layers, and because of this horizontal air movements are almost always more than 10 times greater than vertical movements and sometimes as much as 100 times greater. Consequently, it is usually sufficient to measure only horizontal wind speed. Nevertheless, knowledge of vertical air movements is important for understanding atmospheric phenomena such as cloud formation and local turbulence.

The SPEED OF SOUND is also used to measure wind speed. The sonic anemometer has three approximately U-shaped arms mounted at right angles to one another. The two tips of the arms each carry an acoustic transducer, and the instrument measures the time that an acoustic signal takes to travel from one tip to the other and then back again. A sound wave moves through the air. Consequently, if the air itself is moving, the speed of sound through the moving air will differ from the speed of sound in still air. If the sound wave propagates in the same direction as the wind, its speed will increase, being equal to the sum of the speed of sound and the speed of the wind. If the sound propagates in the opposite direction to the wind, the speed of sound will be reduced by an amount equal to the wind speed. By measuring the speed in both directions between each pair of transducers, the sonic anemometer corrects for the temperature and humidity of the air, which also affects the speed of sound. Because of their reliability and accuracy, sonic anemometers are now used at many weather stations.

Wind profilers (*see* WIND PROFILE) are used to measure wind speeds throughout the troposphere and lower stratosphere (*see* ATMOSPHERIC STRUCTURE).

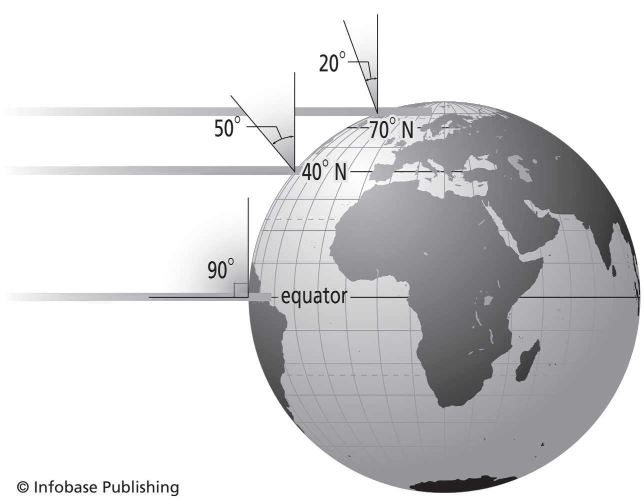
Anemometers must be sited in the open, well clear of obstructions that deflect and slow the wind. For this reason they are usually fixed on tall poles.

Wind speeds measured by anemometers must be recorded to provide data on the winds over a period. Such records are usually made by an anemogram. This is an instrument consisting of a pen linked to an anemometer and a rotating paper drum. The pen makes magnetic contact with the drum and the drum is driven by a motor linked to a clock. The permanent record the anemogram makes of the wind speed is called an anemograph.

angle of incidence The angle at which solar radiation strikes the surface of the Earth. This angle measured is that between the incident radiation and a tangent at the surface; in other words, the height the Sun appears to be in the sky. Because the Earth is almost spherical, at noon at each EQUINOX the angle of incidence is 90° at the equator and elsewhere it is equal to 90° minus the degree of latitude. At latitude 40°, for example, the equinoctial angle of incidence is 50° and at latitude 70° it is 20°.

The angle of incidence also changes with the SEASONS. In latitudes between those of the TROPICS and the Arctic and Antarctic Circles (*see* AXIAL TILT), the maximum seasonal variation at the SOLSTICES is 47°. In latitudes lower than that of the Tropics and higher than that of the Arctic and Antarctic Circles, the maximum variation in the angle of incidence is less than 47°. At the equator, the angle of incidence is never less than 66.5° and the maximum variation is 23.5°. At the Poles, the angle of incidence never exceeds 23.5°.

The angle of incidence determines the intensity of the solar radiation received at the surface. With a high angle of incidence, which occurs when the Sun is high in the sky, a beam of radiation of a given diameter illuminates a smaller area of surface than would a beam of similar diameter with a low angle of incidence, when the is Sun low in the sky. The intensity of the radiation received varies inversely with the area the beam illuminates and, therefore, it is directly proportional to the angle of incidence.



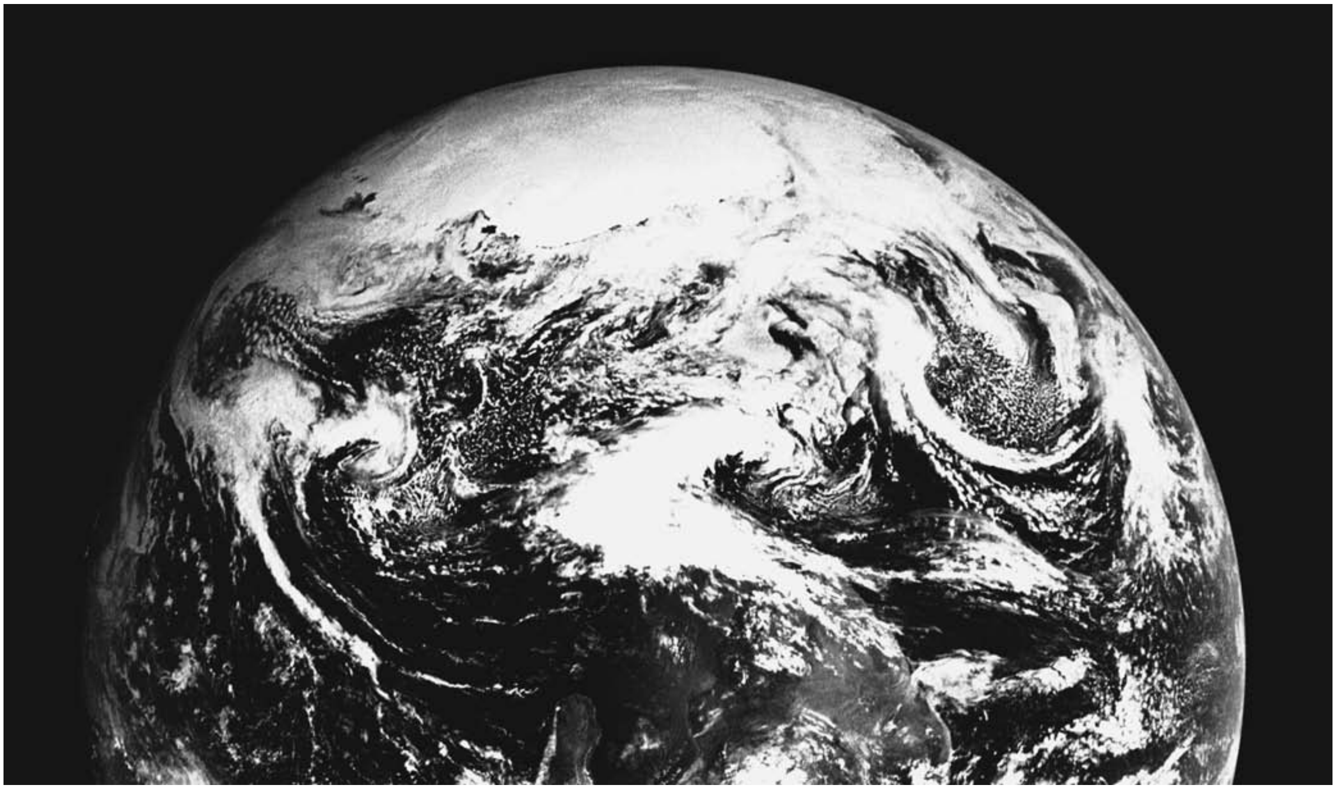
The angle of incidence is the angle at which solar radiation strikes the Earth's surface. This varies with latitude.

anomaly In METEOROLOGY, an anomaly is the deviation of some meteorological feature from the averages that are associated with a particular set of atmospheric conditions. Anomalies can sometimes be predicted. A low ZONAL INDEX in middle latitudes often leads to BLOCKING, for example, which is the anomalous persistence of weather patterns for much longer than is usual.

Varying patterns of SEA-SURFACE TEMPERATURE affect the circulation of air and the location of the JET STREAM over the oceans. In this way they can produce weather anomalies over land.

Antarctic bottom water (**AABW**) A mass of dense water that forms in the Ross and Weddell Seas by the same mechanism that produces the NORTH ATLANTIC DEEP WATER. The freezing of surface water to produce sea ice removes freshwater, increasing the salinity of the adjacent seawater and therefore its density. The temperature of the surface water is slightly above freezing, at which the density of water reaches a maximum. This dense water sinks to the bottom of the Southern Ocean and then moves in an easterly direction around Antarctica, driven by the West Wind Drift (*see* APPENDIX VI: OCEAN CURRENTS). The temperature of the AABW is 28–31°F (between -2 and -0.4°C) and its salinity is 34.66 per mil (parts per thousand).

Antarctic Circumpolar Wave (**ACW**) A set of two atmospheric and oceanic waves that travel through the



Africa and the Arabian Peninsula as they appeared to the crew of the *Apollo 17* spacecraft on December 7, 1972. This was the first occasion on which an Apollo mission followed a trajectory that allowed a view of the South Pole and the Antarctic ice cap. *(NASA)*

Southern Ocean from west to east on a track that takes them all the way around the continent of Antarctica. The waves move at 2.4–3.1 inches per second (6–8 cm/s) and have a period (*see* WAVE CHARACTERISTICS) of 3–5 years. It takes them 8–10 years to complete one circuit of the continent.

As they pass, the waves affect wind speeds, the atmospheric pressure at sea level by up to 8 mb, the SEA-SURFACE TEMPERATURE by about 2.9°F (1.6°C), and the location of the edge of the sea ice by 217 miles (350 km). The cause of the waves is not yet known, but they are believed to arise from instabilities in the relative motions of the West wind drift (*see* APPENDIX VI: OCEAN CURRENTS) and the air above it. The waves affect the climate in latitudes south of about 25°S.

Further Reading

Chung-Chieng, 'Aaron' Lai, and Zhen Huang. "Antarctic Circumpolar Wave and El Niño." Available online. URL: www.ees.lanl.gov/staff/cal/acen.html. Accessed February 13, 2006.

Qiu, B. and F. F. Jin. "Antarctic circumpolar waves: An indication of ocean–atmosphere coupling in the extra-tropics." Available online. URL: www.agu.org/pubs/abs/gl/97GL02694/97GL02694.html. Accessed February 13, 2006.

Antarctic ice sheet An ICE SHEET that covers approximately 97 percent of the land area of Antarctica: 5.5 million square miles (14.2 million km^2). The sheet covers about 5.4 million square miles (13.9 million km^2) to an average depth of 6,900 feet (2,100 m) and contains more than 7 million cubic miles (29 million km^3) of ice.

The ice sheet has three parts. Ice on the Antarctic Peninsula comprises local ice caps, glaciers, and ICE SHELVES. The peninsula extends northward from the continent to within about 600 miles (965 km) of the southern tip of South America.

The main part of Antarctica is divided into two by the Transantarctic Mountains, extending for 1,900 miles (3,057 km). West Antarctica consists of an archipelago of mountainous islands that are covered and bonded together by the ice covering them and the sea between them These comprise the West Antarctic Ice Sheet (WAIS). GLACIERS known as ice streams flow toward the sea from the ice sheet, where the ice forms large ice shelves. The West Antarctic Ice Sheet has been losing mass very slowly for several thousands of years, but in 2001 scientists at NASA's Jet Propulsion Laboratory discovered that within the last 200 years the process has reversed; the WAIS is now thickening. This means that the ice streams have slowed or ceased to move. The ice streams lie at the base of the ice sheet and move because the weight of ice exerts sufficient pressure to melt a thin layer, thus providing liquid water to lubricate the boundary between ice and rock. Scientists suggest that reducing the thickness of the WAIS allowed heat to escape from below the ice sheet and the water froze. If the ice streams remain stationary, the Ross ice shelf will lose its supply of ice and eventually may break up.

East Antarctica is much bigger, with an area of about 3.9 million square miles (10.2 million km^2), and consists of a plateau high above sea level. The East Antarctic Ice Sheet (EAIS) is securely bonded to the underlying rock. There is no possibility that the EAIS will lose a significant amount of mass within the next few centuries.

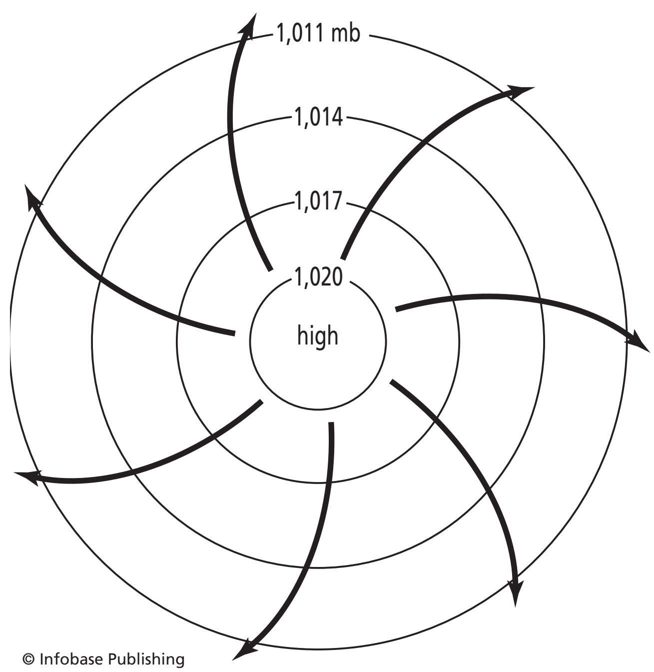
Antarctic intermediate water (**AIW**) A mass of water that forms at the surface of the Southern Ocean, at the ANTARCTIC POLAR FRONT close to latitude 50°S. It then moves northward. Its salinity of 33.8 per mil and low TEMPERATURE, of 36°F (2.2°C), cause it to sink beneath the warmer, less dense water that it encounters. It sinks to about 2,950 feet (900 m) and continues to flow northward. It can be detected as far as 25°N in the North Atlantic.

Antarctic oscillation (**AAO**) A periodic change in the distribution of atmospheric pressure that is believed to occur naturally in the Southern Hemisphere, over the South Pole and over latitude 55°S. It is the counterpart to the ARCTIC OSCILLATION. The AAO is also known as the Southern Annular Mode.

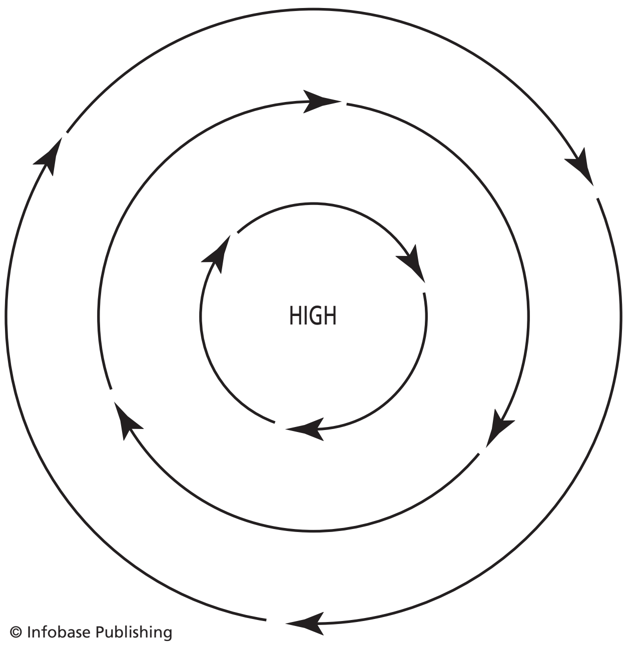
Antarctic polar front (**Antarctic convergence; AAC**) A boundary along the edge of the Southern Ocean, between latitudes 50°S and 60°S, where cold Antarctic water sinks beneath the warmer water in higher latitudes and forms the ANTARCTIC INTERMEDIATE WATER.

anthropogenic An adjective that is applied to substances or processes that are produced by humans or that result from human activities. Strictly, this is an incorrect use of the word, which is derived from *anthropogenesis,* which is the study of human origins. The word is from the Greek *anthropos,* which means "human being", and *gen-*, which means "be produced."

anticyclone A region in which the AIR PRESSURE is higher than it is in the surrounding air; the opposite of a CYCLONE. Pressure is highest at the center of an anticyclone and decreases with distance from the center. Anticyclones range in size from a few hundred miles to as much as 2,000 miles (3,200 km) in diameter. They move more slowly and more erratically than do cyclones.



In an anticyclone, the highest pressure is at the center, and it decreases with distance from the center, as indicated by the isobars. Winds blow outward from the center, moving clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.



Well clear of the surface, the winds flow almost parallel to the isobars, around the center of high pressure. Anticyclonic flow is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

Air flows outward from the region of high pressure toward one of lower pressure at a speed proportional to the PRESSURE GRADIENT. As it moves, the air is subject to the CORIOLIS EFFECT (CorF). This swings it to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The balance between the CorF and the PRESSURE-GRADIENT FORCE produces an anticyclonic circulation.

Anticyclonic is the adjective that describes the direction in which the air flows around an anticyclone. This is opposite to the direction of the Earth's rotation as seen from directly above the North and South Poles. Anticyclonic circulation is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Air also flows anticyclonically around a RIDGE.

At a height of 33 feet (10 m), which is the standard height for observing surface winds, the winds around an anticyclone cross the isobars (*see* ISO-) at an angle of 10° to 30°, depending on local topography and the WIND SPEED. Above the BOUNDARY LAYER the winds flow almost parallel to the isobars at speeds proportional to the pressure gradient.

The high pressure at the center of an anticyclone is produced by the SUBSIDENCE of air. Subsiding air is stable (*see* STABILITY OF AIR). It produces generally clear skies, except where the air is rendered unstable by moving across a warm surface, but the stable air can also produce INVERSIONS and anticyclonic gloom. Winds are usually light and change direction as the anticyclone passes.

Anticyclonic gloom describes the dull conditions that can develop when an anticyclone remains stationary for more than a few days. There is HAZE that reduces VISIBILITY and sometimes a layer of stratocumulus cloud (*see* CLOUD TYPES) that is just thick enough to hide the Sun.

The gloom is the product of subsidence. Air in an anticyclone sinks at a rate of about 3,300 feet (1 km) a day and, if it is unsaturated (as it usually is), it will warm at the dry adiabatic LAPSE RATE of about 17.6°F (9.8°C) a day. The rising temperature in subsiding air sometimes produces a layer of air that is warmer than the air beneath it, forming a type of inversion known as a subsidence inversion. Air trapped beneath the inversion contains all the particles and substances entering the air from the surface. These accumulate, reducing visibility. At the same time, enough water vapor may condense to form a thin layer of cloud immediately below the inversion level. Anticyclonic gloom is best seen from an aircraft flying above and to the side of the affected area.

In middle latitudes, anticyclonic gloom is more likely to form in winter than in summer. In summer, strong solar heating of the ground generates CONVECTION currents that break through the inversion, although the strong sunlight can also supply the energy for reactions among substances held below the inversion to form PHOTOCHEMICAL SMOG. This type of smog frequently occurs over Los Angeles, Mexico City, Athens, and other cities with warm climates, especially those that lie in a natural basin surrounded by higher ground. In the subtropics, where anticyclones are more or less permanent (*see* SUBTROPICAL HIGH), the ingredients that make the gloom are often able to accumulate over a lengthy period.

Summer anticyclones bring fine, warm weather, though with a risk of SHOWERS and THUNDERSTORMS if the air is moist.

In winter, anticyclones in middle and high latitudes are usually associated with polar air (*see* AIR MASS) and bring fine, cold weather. These are called cold anticyclones (cold highs). Air at the center of a cold anticyclone is at a lower temperature than the surrounding air. The SIBERIAN HIGH that forms in winter is an anticyclone of this type. The high pressure at the surface weakens with increasing height and pressure is low in the upper air. A cold anticyclone rarely extends above about 8,000 feet (2,450 m).

The Siberian high is an example of a continental high, which is the persistent area of high air pressure that covers the center of a continent. A continental high also develops over northern Canada. Continental highs are anticyclones consisting of continental polar (cP) air. These AIR MASSES are the principal sources of cold air in the Northern Hemisphere. A continental high also covers Antarctica. That high consists of continental arctic (cA) air.

There are also warm highs. A warm high, also known as a warm anticyclone, warm-core anticyclone, or warm-core high, is an anticyclone that is warmer at its center than it is near the edges.

The stages by which an anticyclone forms or is intensified are known as anticyclogenesis. There are several ways anticyclones can form. In middle latitudes, where families of DEPRESSIONS travel one behind another from west to east, there is often an incursion of polar air behind the last member of the family. This cold, dense air establishes an anticyclone that dissipates with the arrival of the next batch of depressions. Both the depressions and their accompanying anticyclones are related to ridges and TROUGHS in the JET STREAM. The flow of air in the jet stream imparts an anticyclonic motion to the air on its southern side. This is associated with convergence (*see* STREAMLINE) at high level, accompanied by subsiding air and divergence at the surface.

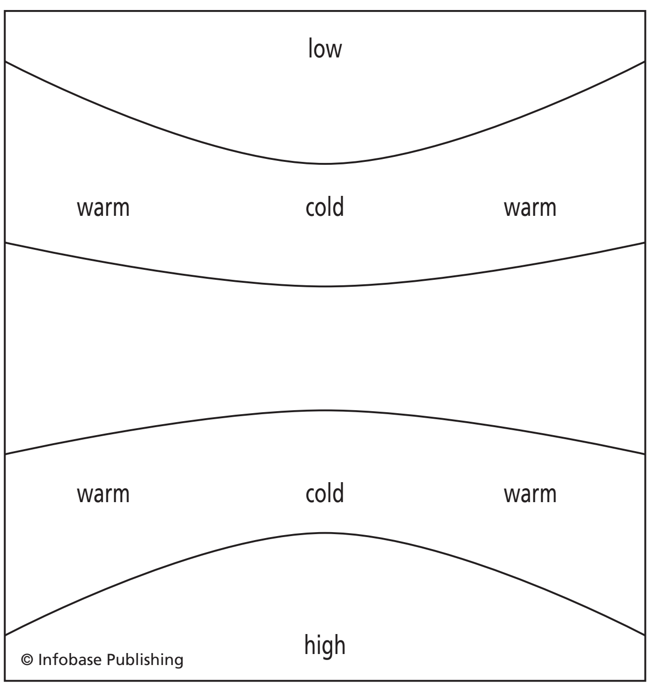
Anticyclones also form in the final stage of the index cycle (*see* ZONAL INDEX). Anticyclones of this type can remain stationary for weeks on end. They are then known as blocking anticyclones.

A cutoff high can also cause BLOCKING. This is a closed, middle latitude anticyclone that has moved into a higher latitude, out of the prevailing westerly air flow, and has become detached from it.

Air that is subsiding on the poleward side of the Hadley cell circulation (*see* GENERAL CIRCULATION) produces anticyclones called subtropical highs.

Anticyclolysis is the weakening and final disappearance of an anticyclone or ridge as air flows outward from it.

Anabaric or *anallobaric* is an adjective applied to any phenomenon that is associated with a rise in atmospheric pressure. The place where the air pressure has risen farther than it has anywhere else over a specified period is called the pressure-rise center, also known as the anabaric center or isallobaric high.

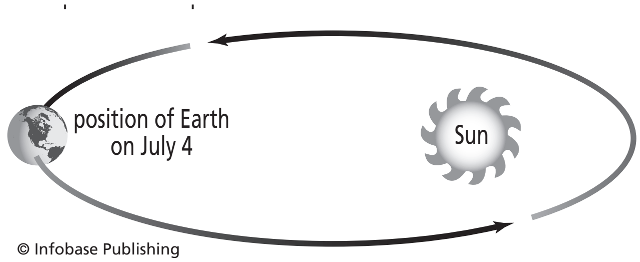


A cold anticyclone develops when high pressure at the surface, produced by a column of cold air, draws air downward, causing the high pressure to weaken with increasing height until low pressure forms in the upper air.

antisolar point The position in the sky that is directly opposite to the Sun. It is in the direction in which shadows point.

antitriptic wind A wind that occurs locally or on a small scale and that is caused by differences in pressure or TEMPERATURE. ANABATIC WINDS, KATABATIC WINDS, LAND AND SEA BREEZES, mountain breezes, and valley breezes are examples of antitriptic winds.

aphelion The point in the eccentric solar orbit of a planet or other body when it is farthest from the Sun. At present, Earth is at aphelion on about July 4, but the dates of aphelion and PERIHELION change over a cycle of about 21,000 years (*see* MILANKOVICH CYCLES and



Aphelion is the position in its elliptical orbit at which a body is farthest from the Sun.

PRECESSION OF THE EQUINOXES). The Earth receives 7 percent less solar radiation at aphelion than it does at perihelion.

aquifer A layer of porous, permeable material (*see* PERMEABILITY) lying below the ground surface that is saturated with water and through which water flows. The water flowing through an aquifer is known as GROUNDWATER and the uppermost limit of the saturated zone is called the water table. The aquifer lies above a layer of impermeable material, such as solid bedrock or compacted clay.

Water drains downward through the soil until it encounters the layer of impermeable material. It can then descend no farther and it accumulates above the impermeable layer, filling all the air spaces, or soil pores, between the mineral particles. The groundwater then flows laterally. Rock strata are rarely horizontal, however, and the water usually flows down the slope. Immediately above the water table, where the soil is unsaturated, water is drawn upward by CAPILLARITY. The layer affected by capillarity is called the capillary layer or capillary zone. Consequently, the water table is not a sharply defined boundary, like the surface of a pond, but a region in which the soil is damp, but not saturated.

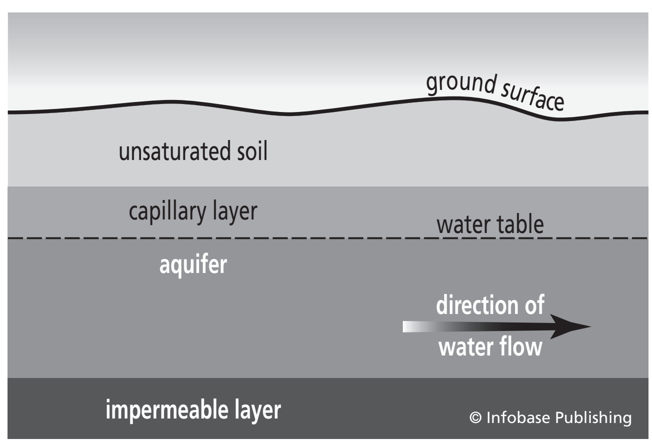
An aquifer may be composed of loose material such as sand or gravel, or of consolidated rock such as sandstone, siltstone, or shale. Sandstone is made from sand grains that have been packed and cemented together. Sand grains range in diameter from 0.002–0.08 inch (62.5 μm to 2,000 μm), siltstone is made from particles less than 0.00016–0.002 inch (4–62.5 μm) across, and shale is made from clay particles, which are less than 0.00016 inch (4 μm) across.

More solid rocks can also form aquifers if they contain fissures and cavities through which water can move. Limestone, for example, is often eroded by acids that are present naturally in water that has percolated through the soil. Over a long period the subterranean erosion of limestone can produce caverns and tunnels carrying underground streams.

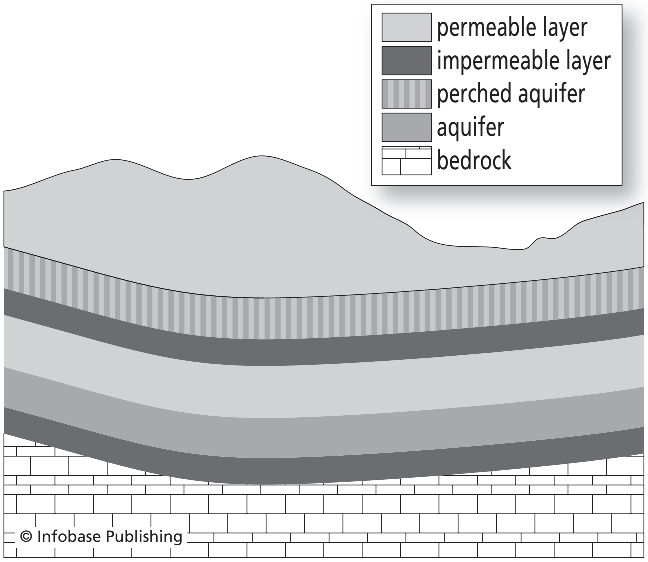
Faulting of the rocks may raise the underlying impermeable layer, causing the upper part of an aquifer to intersect the surface. Where this happens, water flowing through the aquifer will emerge above the ground as a spring or seep.

If there is no impermeable layer above the aquifer, the aquifer is said to be unconfined and water can enter it by draining vertically from the surface. A confined aquifer lies beneath an impermeable layer, so it is sandwiched between two layers of impermeable material. Water cannot enter such an aquifer from directly above, but flows in from the side that is at the higher elevation.

A perched aquifer may lie above a confined aquifer. At the base of the sequence, a layer of impermeable material lies above the bedrock and there is a layer of permeable material above that. Water drains into the permeable layer from outside the area and saturates a band of material above the impermeable layer. This flows as groundwater and comprises the lower aquifer. A second impermeable layer lies above the saturated material, and there is permeable material above that all the way to the surface. Water drains downward through the uppermost layer of permeable material, but is held at the impermeable barrier, where it accumulates



Water drains downward through the soil until it encounters a layer of impermeable material. It accumulates above this layer. The saturated material is the aquifer.



A perched aquifer lies above a layer of impermeable material, with a second sequence of permeable and impermeable layers below. Water enters the lower sequence from outside. Consequently, there are two aquifers, the upper one perched above the lower one.

to form an aquifer lying above the confined aquifer below. This is the perched aquifer.

A rock may be saturated with water, but almost impermeable, making it difficult or impossible for water to flow through it. Such a layer of rock is known as an aquiclude or aquifuge. An aquiclude may form a boundary to an aquifer. If the rock allows water to pass, but only slowly and with difficulty, it is known as an aquitard. An aquitard may form a partial boundary to an aquifer by slowing the movement of water, but without halting it altogether.

Archean The eon of geologic time (*see* APPENDIX V: GEOLOGIC TIMESCALE) that lasted from 3,800 million years ago until 2,500 million years ago. The Archean atmosphere probably consisted of ammonia, methane, and other reducing gases. Modern terrestrial animals, including humans, would have been unable to breathe it. Life first appeared during the Archaean eon.

The oldest known fossils are of bacteria and are about 3,800 million years old. By 2,700 million years ago there were organisms performing PHOTOSYNTHESIS, and during the Archean bacteria capable of photosynthesis formed mounds in coastal waters. Mounds similar to these are found today, in certain shallow, tropical waters. The fossil mounds are known as stromatolites. It was photosynthesis by organisms such as these that began releasing oxygen into the atmosphere, although atmospheric oxygen did not accumulate to anything approaching its present concentration until much later than the Archean.

The Archean was also the time when the surface of the Earth cooled sufficiently for solid rocks to form and for PLATE TECTONICS to commence.

arctic bottom water (ABW) Very cold, dense water that sinks to a depth of about 20,000 feet (6,000 m) in the Greenland and Norwegian Seas, between Greenland and Norway. It fills the basins of those seas, and from time to time spills through narrow channels in the RIDGE that lies between Scotland, Iceland, and Greenland.

arctic high An area of high surface atmospheric pressure that is located over the Arctic Basin. Maritime arctic (mA) air (*see* AIR MASS) covers the basin in summer and continental arctic (cA) in winter, when ice and snow cover the entire surface.

The lower layers of air are cooled by contact with the snow- and ice-covered surface. The low temperature means the air contains little moisture; in winter the mixing ratio near the surface is 0.0016–0.7 ounce of water vapor per pound of dry air (0.1–1.5 g/kg). The dryness of the air means there is little cloud.

Strong cooling from below makes the air very stable (*see* STABILITY OF AIR) and there is often a temperature INVERSION from the surface to about the 850 mb level. The high persists through the summer, but it is weaker and the cold air mass is shallower than in winter.

Arctic Oscillation (AO) A periodic change in the distribution of sea-level atmospheric pressure over the North Pole and over a circle located at about 45°N, the latitude of Minneapolis and Bordeaux, France, and Turin, Italy. When pressure is high over the Pole it is low farther south, and vice versa. The AO is said to be positive when pressure is low over the Pole.

The Oscillation is measured according to an Arctic Oscillation index. The index is high when pressure over the Pole is low and the AO is positive. This condition is also known as the warm phase. When the AO is negative (pressure is high over the Pole) the index is low. A low index is also known as the cool phase.

High sea-level atmospheric pressure farther south strengthens the westerly winds there, and storms travel farther north, affecting Scandinavia and Alaska, but bringing dry conditions to the Mediterranean region and California. Warm air is carried across Eurasia.

When the AO is negative (pressure is high over the Pole), California and the Mediterranean region experience wet weather and the interior of Eurasia is cold. Some climatologists suspect the NORTH ATLANTIC OSCILLATION may be part of the much larger AO.

The AO was negative during the 1980s, but strongly positive throughout the 1990s and until 2005, when it once more became negative. The positive phase may have been responsible for much of the recent warming of the high-latitude Northern Hemisphere. Studies suggest the positive AO accounts for 50 percent of the winter warming over Eurasia during the past 30 years and for 60 percent of the increased rainfall over Scotland and decreased rainfall over Spain observed during the same period.

Scientists believe the positive AO (high index phase) is also responsible for dramatic reductions in the amount of SEA ICE covering the Arctic Ocean that have been recorded during the 1990s. The negative AO (low index phase) produces weak westerly winds that tend to drive sea ice around in circles off the Alaskan and Siberian coasts. This allowed the ice to thicken during the 1980s, but when the AO entered its high index phase the winds strengthened, blowing ice out of the Arctic Ocean through the Fram Strait and into the North Atlantic. Ice that remained was thinner than it had been during the negative AO, and so melted more readily.

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Argo A project that uses free-drifting floats to measure the temperature and salinity of the oceans from the surface down to their operating depth of 6,500 feet (2,000 m), at the same time providing a means of tracking the movement of ocean currents. The first floats were deployed in 2000 and by September 2005 almost 2,000 floats were operational. When the project is fully operational, a total of 3,000 floats will be used, distributed throughout the world's oceans.

Each float is an upright cylinder, 3 feet (90 cm) long, with a 3-feet (90-cm) antenna on top. It contains instruments to measure and record temperature and salinity, a battery-powered pump, and a bladder. The float allows its bladder to fill with water, causing it to sink to its operating depth, where it remains for 10 days, drifting with the ocean current. At the end of this period it pumps the water from its bladder and rises to the surface. At the surface it transmits its data by radio to a receiving station via a satellite link.

Most data on ocean temperature and salinity is obtained from ships. The Argo project allows changes in temperature and salinity and the movement of ocean currents to be monitored away from the main shipping lanes. The Argo floats are made in many countries, but the project is sponsored by the UK Meteorological Office, the Proudman Oceanographic Laboratory, Southampton Oceanographic Centre, and the Hydrographic Office. The University of California at San Diego maintains the Argo Web site. All data from the Argo floats are freely available.

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argon (Ar) A colorless, odorless gas that comprises 0.93 percent of the atmosphere by volume (*see* AIR: ATMOSPHERIC COMPOSITION) and that is considered one of the major atmospheric constituents. Argon is a NOBLE GAS and has no true compounds. It was discovered in 1894 by Lord Rayleigh (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) and Sir William Ramsay.

Argon has atomic number 18, relative atomic mass 39.948, and density (at sea-level pressure and 32°F, 0°C) 0.001 ounces per cubic inch (0.00178 g/cm^3). It melts at -308.2°F (-189°C) and boils at -301°F (-185°C).

aridity Dryness; the extent to which its lack of PRECIPITATION makes a climate incapable of supporting plant growth. Generic types of CLIMATE CLASSIFICA-

Aridity Index

Designation	Description	Aridity Index
r	Little or no water deficiency	0–16.7
s	Moderate water deficiency in summer	16.7–33.3
w	Moderate water deficiency in winter	16.7–33.3
s_2	Large water deficiency in summer	33.3+
w_2	Large water deficiency in winter	33.3+

TION include aridity as one of the principal climatic determinants.

In the THORNTHWAITE CLIMATE CLASSIFICATION the degree of aridity is measured as an aridity index. The index applies only to climates rated as *moist* in the Thornthwaite scheme, because it refers to the growing conditions for farm crops. Moist climates are climate types *A, B,* and C_2, and the aridity index, represented by an additional lower case letter, in two cases with a subscripted number, is added to the designation. Knowing the aridity index for a particular region helps agricultural services in advising farmers and ensures adequate supplies of seeds for crop varieties suited to the growing conditions.

The aridity index is calculated as $100W_d/PE$, where W_d is the water deficit (*see* SOIL MOISTURE) and PE is the potential EVAPOTRANSPIRATION. The table shows how the index is applied.

aspect The direction that sloping ground faces. This determines its exposure to direct sunlight and, therefore, the type of vegetation it will support.

Sloping ground that faces in the direction of the equator and receives the greatest exposure to sunlight possible is described as adret. In the Northern Hemisphere an adret is a south-facing slope.

The opposite slope is described as ubac. An ubac slope faces away from the direction of the equator and therefore is shaded. In the Northern Hemisphere an ubac is a north-facing slope.

Both adjectives, *adret* and *ubac,* were first applied to land on the sides of valleys in the European Alps. Ubac slopes, being shaded and generally cool, tended to remain forested. Sunnier, warmer adret slopes were more likely to be cultivated. Dwellings were built on adret slopes and that is where villages grew up.

Atlantic high An ANTICYCLONE that covers a large part of the subtropical North Atlantic Ocean. There is a similar anticyclone over the South Atlantic. The Atlantic highs are source regions for maritime AIR MASSES. The North Atlantic and PACIFIC HIGH together cover one-quarter of the Northern Hemisphere and for six months of each year they cover almost 60 percent of it.

Atlantic Multidecadal Oscillation (AMO) A change in the climate over the North Atlantic Ocean that occurs over a cycle of about 50–70 years. This has been detected over several centuries. The AMO comprises shifts in sea-surface temperature to either side of the mean between the equator and latitude 70°N. It is thought to drive the THERMOHALINE CIRCULATION.

Scientists suspect that marked fluctuations in the summer climates of North America and western Europe during the 19th century may have been linked to the AMO. The AMO was in a warm phase during the late 19th century and from 1931 until 1960. It was in a cool phase from 1965 until 1990. SEA-SURFACE TEMPERATURES change by up to approximately 0.5°F (0.3°C) due to the AMO, the largest temperature changes occurring to the east of Newfoundland.

The AMO was first noted in 1964 by Jacob Bjerknes (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), who suggested that the slow warming of surface waters in the 1910s and 1920s might have been caused by a surge of warm water carried by the Gulf Stream (*see* APPENDIX VI: OCEAN CURRENTS). By the 1940s the surge had produced high global air temperatures. A sharp cooling which ended in the 1980s followed the period of high temperatures.

An index of the AMO is said to be positive when temperatures are higher than average and negative during cool periods. Large-scale droughts in the United States, such as occurred in the 1930s, 1950s and 1960s, and from 1996 to 2004, appear to be related to a positive AMO index. When the AMO index is negative, the United States experiences wet weather. The AMO is also thought to influence the strength of El Niño and La Niña episodes (*see* ENSO).

The temperature changes involved are of several tenths of a degree Celsius to either side of the mean. It is thought that the AMO is linked to the North Atlantic Oscillation and Arctic Oscillation, but in ways that are not understood.

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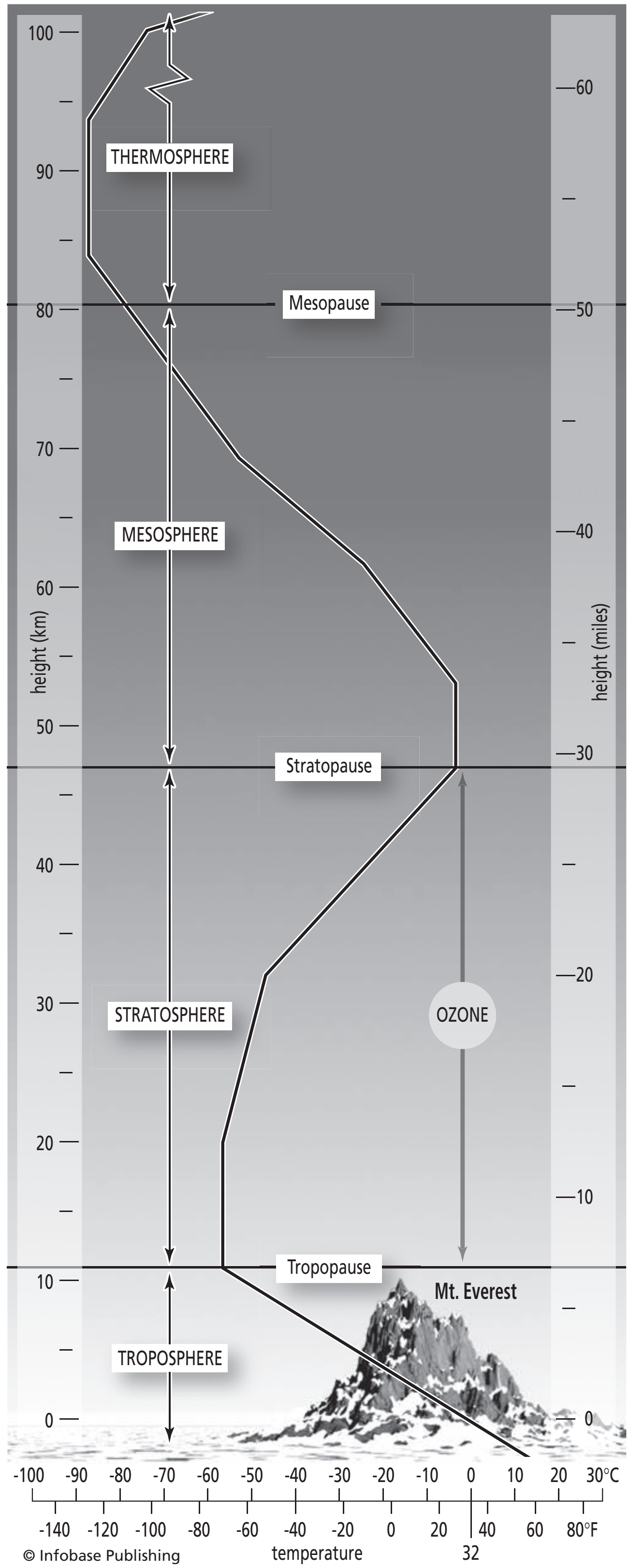
atmospheric chemistry The scientific study of the chemical composition of the atmosphere (*see* air: atmospheric composition) and of the chemical processes that occur within it. Scientists in past centuries who were studying the gases present in the air generated much of the present knowledge and understanding of gases in general and of the process of combustion.

The atmosphere has not always had its present composition and atmospheric chemists have studied the stages by which that composition evolved (*see* air: evolution of the atmosphere). Today, atmospheric chemists are especially concerned with the fate of pollutants released into the air (*see* air pollution and ozone layer) and with the chemical behavior of gases that absorb radiation (*see* greenhouse effect: global warming potential).

atmospheric structure Conditions in the atmosphere do not remain constant, or change at a constant rate, all the way from the surface of the Earth to its uppermost limit at the edge of outer space. Rather, the atmosphere is layered, with each layer forming a shell around the Earth and, except for the outermost shell, enclosed by

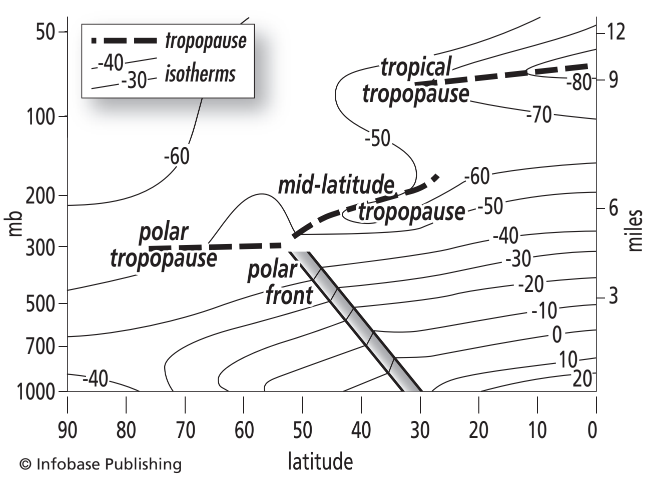


The atmosphere consists of a series of layers, one outside the other, and identified mainly by the way temperature changes with height within them.

the shell outside it. Each layer is known as an atmospheric shell or atmospheric layer.

There is no precise upper boundary to the atmosphere. About 90 percent of its total mass lies between the surface and a height of about 10 miles (16 km), and half of its mass is in the layer below about 3.5 miles (5.5 km). Above 10 miles, the remaining one-tenth of the atmospheric mass extends to a height of at least 350 miles (550 km), although the density of the air there is about one million-millionth (one trillionth) of the density at sea level. Beyond that height the atmosphere merges imperceptibly with the atoms and molecules of interplanetary space, and especially with the outer fringes of the Sun's atmosphere.

The lowest layer of the atmosphere is called the troposphere. In this layer the air temperature decreases steadily with height at a rate known as the LAPSE RATE, which varies from place to place and from time to time. The troposphere is the layer in which vertical and horizontal currents cause the air to be turbulent, and it is the layer that contains virtually all of the atmospheric water vapor. The turbulent transport of heat by the movement of air, combined with the vertical transport of heat by the EVAPORATION of surface water and the CONDENSATION of water vapor to form clouds and deliver precipitation, make the troposphere the atmospheric layer in which all weather phenomena occur.



This diagram shows the height of the tropopause at different latitudes. It shows pressure along the left vertical axis, height along the right vertical axis, and latitude along the horizontal axis. The diagram relates pressure, height, and latitude to temperature.

The lowest part of the troposphere, where the movement of air is strongly affected by its contact with the surface, comprises the PLANETARY BOUNDARY LAYER. The whole of the troposphere, including the planetary boundary layer, is called the lower atmosphere. The upper part of the troposphere is called the upper air. There is no definite height at which the upper air commences, but the lowest upper-air charts (*see* WEATHER MAP) typically depict conditions at a level where the AIR PRESSURE is 925 mb (27 inches of mercury, 13.4 lb/in^2).

The upper atmosphere comprises the whole of the atmosphere that lies above the tropopause. Upper atmosphere and upper air are not synonymous.

The upper boundary of the troposphere is called the tropopause. This is almost horizontal and is clearly defined. Below the tropopause, the air temperature decreases with height. Above the tropopause, there is sometimes a temperature INVERSION, but there is always a layer in the lower stratosphere where the temperature remains constant with height—an isothermal layer. Air is able to rise through the troposphere by CONVECTION, but it is unable to cross the tropopause, because its temperature and density are then equal to those of the surrounding air. Since air cannot cross the tropopause, neither can water vapor, AEROSOL particles, or other substances carried in the air. Very large cumulonimbus clouds (*see* CLOUD TYPES) may generate vertical air currents that are vigorous enough to create tropopause breaks that penetrate the tropopause, carrying moisture into the stratosphere, and violent VOLCANIC ERUPTIONS can inject both gases and particles. Apart from these exceptions, however, water vapor and particles are held below the tropopause and stratospheric air is extremely dry.

A tropopause break is a discontinuity in the tropopause through which tropospheric air and water vapor is able to cross into the stratosphere, and stratospheric OZONE sometimes enters the troposphere. Breaks occur where the north–south temperature gradient is most sharply defined, at about latitudes 30° and 50°N and S. A downward depression in the tropopause that brings stratospheric air into the troposphere, and sometimes as far as the surface, is known as a tropopause fold. The stratospheric air is very dry and enriched in ozone.

The height of the tropopause varies according to the vigor of the convective air movements in the troposphere. These are most vigorous in the TROPICS and least vigorous in the Arctic and Antarctic. Consequently, the height of the tropopause averages about 10 miles (16 km) over the equator, 7 miles (11 km) in middle latitudes, and 5 miles (8 km) at each pole. Pressure at the tropopause ranges from about 100 mb at the equator to about 300 mb at the poles, reflecting the greater height of the equatorial tropopause.

Temperature decreases with height throughout the troposphere. Consequently, the deeper the troposphere, the lower the temperature will be at the top. This means that the decrease in surface temperature from the equator to the poles is reversed at the tropopause. The average temperature at the tropopause is -85°F (-65°C), over the equator, about -67°F (-55°C), in middle latitudes, and over the poles it is about -22°F (-30°C).

Substratosphere is a name sometimes given to the uppermost part of the troposphere, lying immediately below the tropopause. Air in this layer is cold, dry, and similar to the air above it in the lower stratosphere.

The tropopause forms a very effective physical boundary. Tropospheric air rarely crosses it and only under special circumstances. It is equally difficult for material to cross it in the opposite direction. Volcanic eruptions can project particles of ash and sulfate through the tropopause, but when they do so it can take a long time, sometimes several years, for the particles to fall back into the troposphere.

The atmospheric layer above the tropopause is the stratosphere. Any interaction between disturbances on either side of the tropopause is called stratospheric coupling.

In the lower stratosphere, temperature remains constant with height. This is known as the isothermal layer. Then, at about 12 miles (20 km) the temperature begins to increase with height, and at about 20 miles (32 km) it increases more rapidly, by up to about 2.2°F per 1,000 feet (4°C per km) and sometimes exceeds 32°F (0°C). The temperature continues to increase with height all the way to the upper boundary, the stratopause.

The warming is due to the absorption of solar ULTRAVIOLET RADIATION by oxygen and ozone. The OZONE LAYER, 66,000–98,000 feet (20–30 km) above sea level, where the concentration of ozone (O_3) is higher than it is elsewhere, is located in the stratosphere; this region is sometimes called the ozonosphere.

The temperature profile is generally true only in summer, however, and is not the same at all latitudes. In winter, the tropopause is at its maximum height above the equator and the average temperature is -112°F (-80°C). This is also the temperature in the middle stratosphere at high latitudes, but there is a warm region between 50° and 60° N and S, where the temperature averages about -58°F (-50°C). During the winter, the temperature in the stratosphere sometimes rises by as much as 70°F (39°C) over a few days, then falls again.

There are strong winds just above the tropopause, but the air is generally calm at higher levels although stratospheric winds do occur. The little that is known about this air movement has been obtained from satellite observations of the way particles are distributed following a major volcanic eruption. There were two significant eruptions in 1991. Mount Pinatubo, located in the Philippines at 15.15°N, erupted in June, and Cerro Hudson, in Chile at 45.92°S, erupted in August. Both volcanoes injected ash and sulfur dioxide into the stratosphere. The cloud from Mount Pinatubo traveled westward, spreading to the north and south as it did so. The cloud from Cerro Hudson traveled eastward and did not widen. The movement of these clouds indicates that in the Northern Hemisphere low-latitude stratospheric winds blow predominantly from west to east and those in the middle latitudes of the Southern Hemisphere blow from east to west. Very little material from Cerro Hudson reached Antarctica, illustrating the extent to which stratospheric air over the southern polar region is isolated during the late winter (August and September). This isolation from air in lower latitudes prevents air that contains ozone from entering the polar stratosphere and replenishing the depleted ozone layer.

In summer, the base of the stratopause is at a height of about 34 miles (55 km) over the equator and poles and about 31 miles (50 km) in middle latitudes. In winter, it is at about 30 miles (48 km) over the equator and 37 miles (60 km) over the poles. The atmospheric pressure at the stratopause is about 1 mb—one-thousandth of the sea-level pressure. Like the tropopause, the stratopause is a region where temperature ceases to change with height. The temperature maximum that occurs in the upper stratopause is sometimes called the mesopeak, at a height of about 50 miles (80 km). There temperatures reach about 80°F (27°C, 300K).

That part of the atmosphere in which the chemical composition of the air is homogenous (uniform) is called the homosphere. This is the lower part of the atmosphere, comprising the troposphere and stratosphere, extending from the surface to a height of approximately 30–40 miles (50–65 km).

Only about 0.1 percent of the mass of the atmosphere is located above the stratopause. The layer above the stratopause is called the mesosphere. The mesosphere is also known as the upper mixing layer. This is the region through which there is a rapid decrease of temperature with height, associated with considerable turbulence that mixes the constituents of the atmosphere. The temperature continues to fall with height rapidly all the way to the mesopause, above which lies the thermosphere. The base of the mesopause is about 50 miles (80 km) above sea level and it extends to a height of about 56 miles (90 km). The temperature within the mesopause remains constant with height and is usually about -130°F (-90°C) in winter, although it can be lower. In summer, the temperature can rise to approximately -22°F (-30°C).

The thermosphere is the uppermost layer of the atmosphere, and it has no precise upper margin. Although the gases composing it are extremely rarefied, they do exert drag on spacecraft at heights of more than 155 miles (250 km). The lower thermosphere consists mainly of molecular nitrogen (N_2) and molecular (O_2) and atomic (O) oxygen. Above 125 miles (200 km) there is more atomic oxygen than molecular or atomic (N) nitrogen. Higher still the most abundant (but extremely tenuous) gas is atomic helium (He), and above that there is atomic hydrogen (H). That part of the atmosphere, above a height of about 50 miles (80 km), which has a heterogeneous (nonuniform) composition is called the heterosphere.

The temperature remains constant with height in the lower thermosphere, but at about 55 miles (88 km) it begins to increase rapidly with height. The rise in temperature is due mainly to the absorption of ultraviolet radiation by atomic oxygen. The temperature refers only to the estimated speed of particles, however, because the atmosphere is so tenuous that satellites orbiting in it are not warmed by the air, although they are warmed by the solar radiation they absorb.

At the thermopause, which is the upper boundary of the thermosphere, the temperature is sometimes more than 1,830°F (1,000°C). The thermopause is between 310 and 620 miles (500–1,000 km) above the surface, its height varying with the intensity of the sunlight.

The region of the atmosphere in which the equilibrium of the air is maintained mainly by convection is sometimes known as the turbosphere. Air in the turbosphere is being constantly mixed by vertical convective motion, so within the turbosphere the layering of air is based on its density, rather than the molecular weight of its constituent gases. The turbosphere extends from the surface to a height of about 60 miles (100 km), although its upper boundary, called the turbopause, is poorly defined. Above the turbopause the equilibrium of air is not maintained by convection and air molecules move by DIFFUSION, which causes them to form layers according to their weights. Heavier gases lie beneath lighter gases in the heterosphere. Above about 75 miles (120 km) PHOTODISSOCIATION by solar ultraviolet radiation separates oxygen molecules (O_2 + photon (UV) $\rightarrow$ O + O), and more than half of the oxygen is present as single atoms.

Upper-atmosphere dynamics describes the movement of air in the upper atmosphere (all of the atmosphere above the tropopause), but especially at heights of more than 300 miles (500 km), where the motion consists predominantly of ATMOSPHERIC TIDES, ATMOSPHERIC WAVES, TURBULENT FLOW, and sound waves.

The ionosphere is a layer of the atmosphere in which photoionization (*see* ION) causes the separation of positively-charged ions and negatively-charged electrons. Because ionization is maintained by solar radiation, the thickness of the ionosphere and the density of ions within it vary daily, seasonally, and with latitude. Generally, the ionosphere extends from a height of about 37 miles (60 km) to about 620 miles (1,000 km), although the ion density is greatest from about 50 miles (80 km) to 250 miles (400 km).

The ionosphere is subdivided into four layers, designated D, E, F_1, and F_2, in ascending order of height. The D and E layers disappear at night, except in very high latitudes, as ionization ceases and collisions between existing ions cause them to recombine. At greater heights, where the atmosphere is so rarefied that collisions are less common, ions survive at night. Ions survive in very high latitudes because of the ionizing effect of the interaction of the SOLAR WIND and the MAGNETOSPHERE. In these latitudes aurorae (*see* OPTICAL PHENOMENA) are produced in the ionosphere. The ionosphere reflects radio waves. Waves at the lowest frequencies are reflected in the D and E layers, waves at higher frequencies in one or other of the F layers. The F layers are also known as the Appleton layer. It is named after the Scottish physicist Sir Edward Appleton (1892–1965), the inventor of RADAR.

The atmospheric shell around the Earth that extends from the surface to the base of the ionosphere is sometimes called the neutrosphere. Within the neutrosphere most of the constituents of the atmosphere are electrically neutral.

In the exosphere, which is the outermost layer of the atmosphere, the atoms and molecules of the air are so widely dispersed that collisions between them are rare events. The uppermost part of the exosphere, where individual atoms may never collide, is known as the fringe region or spray region. Theoretically, atoms in the fringe region can escape into space without experiencing a collision. Those that do not escape move in free orbits about the Earth at speeds determined by their most recent collision.

The whole of the atmosphere, together with the adjacent region of space in which satellites orbit, is known as aerospace. Airspace is the air, extending from the surface to the uppermost limit of the atmosphere, above the surface area of a territory or nation. A nation exercises sovereignty over its airspace, allowing it to permit or forbid aircraft to enter it and to control aircraft movements within it. This concept of sovereign airspace was first defined in the Paris Convention on the Regulation of Aerial Navigation (1919) and was restated in 1944 in the Chicago Convention on International Civil Aviation. The powers exercised by the civil authority within national airspace are equivalent to those that apply in territorial waters as set out in the Geneva Convention on the High Seas (1958).

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atmospheric tides TIDES that occur in the atmosphere. Like ocean tides, atmospheric tides are produced by the gravitational attraction of the Moon and Sun, but because air is much less dense than water the gravitational effect on the atmosphere is small and atmospheric tides are much less evident than are ocean tides. The maximum value is at the equator, where the tidal variation in surface AIR PRESSURE never exceeds 0.4 pounds per square foot (20 Pa). It can be measured as a twice-daily variation in atmospheric pressure, averaged over a long period, that coincides with the lunar orbit.

The Sun exerts a much stronger effect, however, producing a maximum pressure every morning and evening between about 9 A.M. and 10 A.M. local time. Because the Sun is much farther from the Earth than is the Moon, and gravity is subject to the INVERSE SQUARE LAW, the gravitational force exerted at the surface of the Earth by the Sun is only about 47 percent of that exerted by the Moon. Despite this, the pressure difference due to the solar atmospheric tides is almost 6.3 pounds per square foot (300 Pa), which is 15 times greater than that produced by the lunar tides.

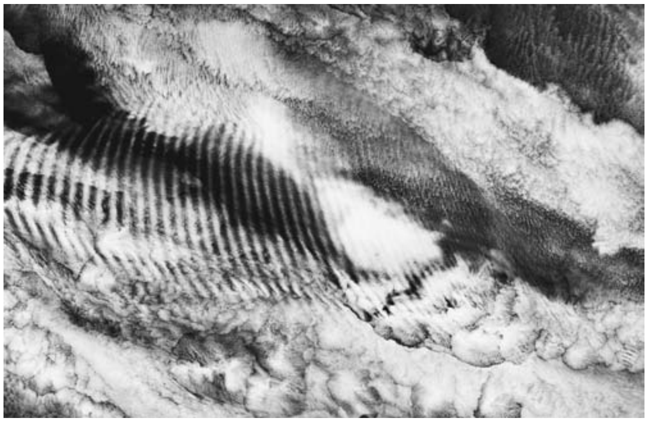
The difference is due to the heating effect that is exerted by the Sun, but not by the Moon. This produces what are sometimes called thermotidal oscillations. Heating produces a strong pressure contrast between day and night that propagates as a wave around the world. The atmospheric wave moves vertically as well as horizontally. The combination of the horizontal and vertical expansion and contraction of the atmosphere produces a cycle with a period of half a day, just like that of the gravitational tides.

The magnitude of the lunar atmospheric tide, which is that part of the atmospheric tides caused by the gravitational attraction of the Moon, is very small. It can be detected only by careful analysis of records of atmospheric pressure made by readings taken at hourly intervals over a long period. The hourly readings must then be related to lunar time. The largest lunar tide detected in this way is a fluctuation of 0.003 pounds per square inch (20 Pa, 0.003 mb).

The amplitude (*see* WAVE CHARACTERISTICS) of the atmospheric tides is greatest at the equator. Away from the equator it is reduced by the CORIOLIS EFFECT, and in middle and high latitudes the passage of ordinary weather systems produces such large pressure changes that the tides cannot be detected directly, but only by statistical analysis of pressure records over a long period.

The propagation of atmospheric tides is felt as a very light wind. It is light because the strength of a wind is proportional to the PRESSURE GRADIENT, and the tides produce only a very small difference in pressure over a very large distance. At the surface, the tidal wind rarely blows at more than about 2 MPH (1 m/s).

In the upper atmosphere, the tidal wind is stronger. As the expansion of the atmosphere causes the density of the air to decrease, the wind accelerates in order to conserve energy (*see* THERMODYNAMICS, LAWS OF). At a height of 30 miles (50 km) it can accelerate by more



The ripples in these stratocumulus clouds over the Indian Ocean, similar to those produced when a pebble is thrown into a pond, are caused by gravity waves. The clouds beneath the waves are associated with sinking air that is strongly cooled at the level of the cloud tops. This natural-color image was acquired on October 29, 2003, by the Multi-angle Imaging SpectroRadiometer (MISR). ***(NASA MISR team)***

than 20 MPH (9 m/s) and at 60 miles (100 km) by more than 110 MPH (50 m/s).

atmospheric wave A vertical displacement in stable air (*see* STABILITY OF AIR) in the PLANETARY BOUNDARY LAYER that occurs at a height of 500–650 feet (150–200 m). It resembles the internal waves that occur beneath the surface of the sea.

Acoustic sounders are used to detect atmospheric waves. Acoustic sounders are instruments that transmit sound waves with a wavelength (*see* WAVE CHARACTERISTICS) of about 4 inches (10 cm) and detect the BACKSCATTER from layers of air with different densities.

Most atmospheric waves are gravity waves. These form when air is displaced upward by passing over a surface obstruction, as happens, for example, when air crosses a mountain. The displaced air enters a region where the air is less dense and therefore sinks by gravity, but the sinking air overshoots and enters denser air, causing it to rise again.

Other atmospheric waves are caused by WIND SHEAR and superficially resemble breaking waves on the sea surface. If the wind blows at different speeds on either side of a layer, the wind shear produces an instability that make the layer oscillate up and down. It is the same mechanism that causes a flag to flap in the wind, but it operates in a horizontal rather than vertical plane. The height of the waves is restricted by the stability of the air, which acts to restore the displaced air to its original level.

attenuation The weakening of a signal with increasing distance from its source. Attenuation is caused by the absorption of part of the signal's energy by the medium through which it travels and by divergence of the signal, which spreads its energy over an increasing area.

Attenuation can be seen in the ripples that are produced on a pond by dropping a stone into the water. As the circle of ripples spreads, the length of the wave front (*see* WAVE CHARACTERISTICS) increases, because the wave front is the circumference of the growing circle. No more energy is added to the waves, so the original energy is spread increasingly thinly. The consequence is that the amplitude of the waves decreases (they grow smaller) until, at a certain distance from the source, no waves can be seen.

Automated Surface Observing Systems (ASOS) A network of about 1,000 stations across the United States, comprising instruments that automatically make almost continuous measurements of surface AIR PRESSURE, TEMPERATURE, WIND SPEED and direction, runway VISIBILITY, the height of cloud ceilings, CLOUD TYPES, and intensity of PRECIPITATION.

ASOS units are designed to provide meteorological information for airports and are augmented by a separate system to provide warning of THUNDERSTORMS. ASOS is operated by the NATIONAL WEATHER SERVICE, and the thunderstorm facility is run in collaboration with the Federal Aviation Administration.

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avalanche A mass of material that is descending at high speed down a mountainside. The word usually refers to moving snow, but it can also be applied to ice, earth, rock, or to any mixture of these.

Snow will not accumulate on a steep slope or on a slope that is less steep but slippery because it is covered with grass. That is because its own weight makes the snow slide away harmlessly. Snow can accumulate to a considerable depth on a very shallow slope, but because the underlying surface is almost horizontal the snow remains stable and will not slide. Avalanches are a risk on intermediate slopes, with a gradient of about 30° to 40°. This gradient is neither so steep as to prevent snow accumulating, nor so shallow as to allow it to accumulate safely.

An avalanche occurs when the layer of snow becomes unstable. There are three ways this can happen. The addition of more snow, due to a heavy fall of snow or the deposition of wind-driven snow, increases the weight of the layer. Alternatively, the snow layer may lose its adhesion to the underlying surface. This can happen if a sudden warming in spring or from a FÖHN WIND melts some of the snow at a higher level, sending a stream of water beneath the snow that lies farther down the slope. It can also happen that the bonds between snow grains weaken naturally, so the cohesive strength of the mass of snow decreases. Once the layer is unstable the slightest vibration may dislodge it. A passing skier, a gunshot, or the loud snap of a breaking tree branch may be all that is needed.

There are two types of snow avalanches. In a point-release avalanche, the disturbance causes just a few snow grains to move. These dislodge other grains below them and the disturbance grows rapidly. The resulting avalanche has the shape of an inverted V and it involves only the surface layer of snow.

The much more dangerous type of avalanche moves an entire slab of snow. A slab avalanche has an approximately rectangular shape and is up to half a mile (800 m) wide. It occurs when the mass of snow has already crept a little way down the slope. Its sides and base are under stress, and when a vibration disturbs it, that stress is released suddenly and the entire mass moves as a single unit.

As an avalanche slides and falls down the slope, it gathers more snow and it accelerates. The fastest speeds are attained when the snow is dry and powdery, because there is a great deal of air between the grains of powdery snow and this reduces friction between snow grains. Speeds of 80–100 MPH (130–160 km/h) are common, and avalanches have been known to reach 145–190 MPH (235–300 km/h). Wet snow moves more like mud, flowing down the slope rather than bounding down it, and it travels more slowly, rarely exceeding about 55 MPH (88 km/h).

Avalanche Classes

(There are five classes. Each class is 10 times stronger than the one preceding it.)

Class	Damage	Path Width
1	Could knock someone over, but not bury them.	33 feet (10 m)
2	Could bury, injure, or. kill someone	330 feet (100 m)
3	Could bury and wreck a car, damage a truck, demolish a small building, break trees.	3,330 feet (1,000 m)
4	Could wreck a railroad car or big truck, demolish several buildings, or up to 4 ha (10 acres) of forest.	6,560 feet (2,000 m)
5	Largest known; could destroy a village or up to 40 ha (100 acres) of forest.	9,800 feet (3,000 m)

An avalanche is very destructive. Even a small one can have an impact of 0.1–0.5 ton per square foot (900–4,500 kg/m^2). That is sufficient force to destroy a timber chalet. A major avalanche can exert a force of more than 9 tons per square foot (8,000 kg/m^2). That will uproot trees and demolish solidly constructed buildings.

Avalanches are graded according to their destructive force and width. The table above lists the five categories.

Small avalanches are sometimes triggered deliberately by explosives to prevent snow accumulating to a depth that could cause a major avalanche. Strong fences to hold the snow are built across slopes where avalanches are likely to begin.

As it slides down the mountainside, the mass of snow and debris pushed air ahead of itself, generating an avalanche wind. A major slab avalanche can generate a wind of up to 185 MPH (300 km/h). This wind, comparable in strength to the wind of a category 5 hurricane, can cause serious structural damage to buildings, so they are already weakened when the snow reaches them.

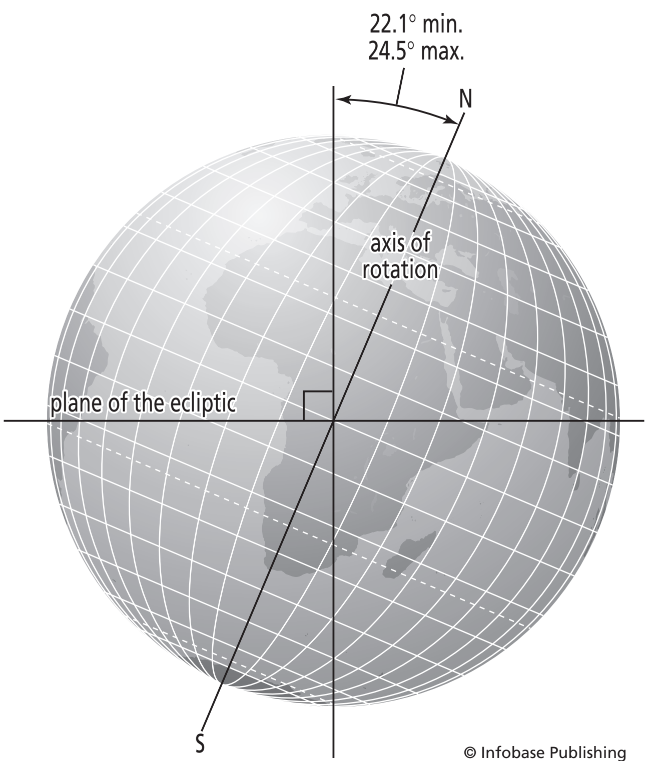
Avogadro's law The law stating that provided they are at the same temperature and pressure, equal volumes of all gases contain the same number of smallest particles. The smallest particles are atoms or molecules and the number per mole (*see* UNITS OF MEASUREMENT) is known as the Avogadro constant. The law was proposed in 1811 by the Italian physicist Count Amedio Avogadro (1776–1856).

The value of Avogadro's constant is 6.02252×10^{23}. That is the number of atoms or molecules in one mole of a substance. It is symbolized by N_A or L.

The optical effect produced by a March sunset at South Pole Station, Antarctica, 1979, with the Sun actually below the horizon. ***(Commander John Bortniak, NOAA Corps)***

axial tilt The angle between the Earth's axis of rotation and a line passing through the center of the Earth that is at right angles to the PLANE OF THE ECLIPTIC. It is because of the axial tilt that the climates of the Earth experience SEASONS that become increasingly pronounced with distance from the equator.

The Earth's axial tilt varies over a cycle of about 41,000 years from a minimum of 22.1° to a maximum of 24.5°. At present the tilt is 23.45°. The axial tilt determines the location of the TROPICS, which are at 23.5°N and 23.5°S, and the height of the Sun above the horizon at the summer SOLSTICE over the poles, which is also 23.5°.



The tilt of the Earth's axis is the angle between the rotational axis and a line passing through the center of the Earth at right angles to the plane of the ecliptic. The tilt varies from 22.1° to 24.5°.

The Arctic and Antarctic Circles, at latitudes 66.5° N and S, are the lines that mark the boundary of regions within which there is a period in winter when the Sun does not rise above the horizon and a period in summer when it does not sink below it. The location of these lines is also determined by the Earth's axial tilt: $66.5 = 90 - 23.5$. At the Arctic and Antarctic Circles themselves, the periods of "midnight Sun" and "midday darkness" are confined to the two days of the winter and summer solstices. At higher latitudes, the period of continuous darkness and continuous daylight lasts for longer. At the summer solstice, the Sun is no higher than 47° above the horizon anywhere inside the Arctic or Antarctic Circles.

The contrast between summer and winter is greatest when the tilt is greatest, and if the axis were not tilted there would be no seasons. The cyclic change in the axial tilt is one of the factors in the MILANKOVITCH CYCLES that are linked to the onset and ending of ice ages.

azimuth The angle between two vertical planes, one of which contains a celestial body or satellite and the other the meridian on which an observer is located. The azimuth is commonly used for reporting the position of satellites and is equal to the number of degrees from north (0°) counting in a clockwise direction. If the azimuth of a satellite is reported as, say, 170°, this means the satellite will be found by measuring 170° clockwise from north, so it will be 10° to the east of south.

Azores high Part of the ATLANTIC HIGH that is centered above the Azores, a group of islands situated about 800 miles (1,290 km) to the west of Portugal. The ANTICYCLONE often extends westward as far as Bermuda, when it is known in North America as the Bermuda high. The difference in atmospheric pressure between the Azores high and the ICELANDIC LOW drives weather systems from west to east across the North Atlantic Ocean. Periodic variations in this pressure difference are known as the NORTH ATLANTIC OSCILLATION.

B

backscatter The proportion of a signal that is scattered (*see* SCATTERING) from the surface at which the signal is directed. The signal may be an electromagnetic wave, such as RADAR, or acoustic. Acoustic signals are used to study ATMOSPHERIC WAVES, for example.

The amount of backscatter can be calculated by comparing the strength of the transmitted signal with the strength of the signal reflected from the surface to the receiver, after making allowance for ATTENUATION and absorption by the medium through which the signal travels.

bacteria Living organisms that in the widely-used five-kingdom classification system comprise one of the kingdoms, Bacteria, in the superkingdom Prokarya; in the alternative three-domain classification, Bacteria comprise the only kingdom in the domain Eubacteria. Most bacteria consist of a single cell.

Bacteria are present almost everywhere, and some species play an important role in decomposing organic wastes and in the cycling of nutrients (*see* NITROGEN cycle and CARBON CYCLE). Decomposition involves the oxidation of carbon present in biological molecules to CARBON DIOXIDE that is released into the air between soil particles or that dissolves in water and eventually returns to the atmosphere. Many bacteria can survive long periods in a dormant state, as SPORES. Bacteria and their spores can be transported long distances as part of the aerial plankton (*see* AEROSOL).

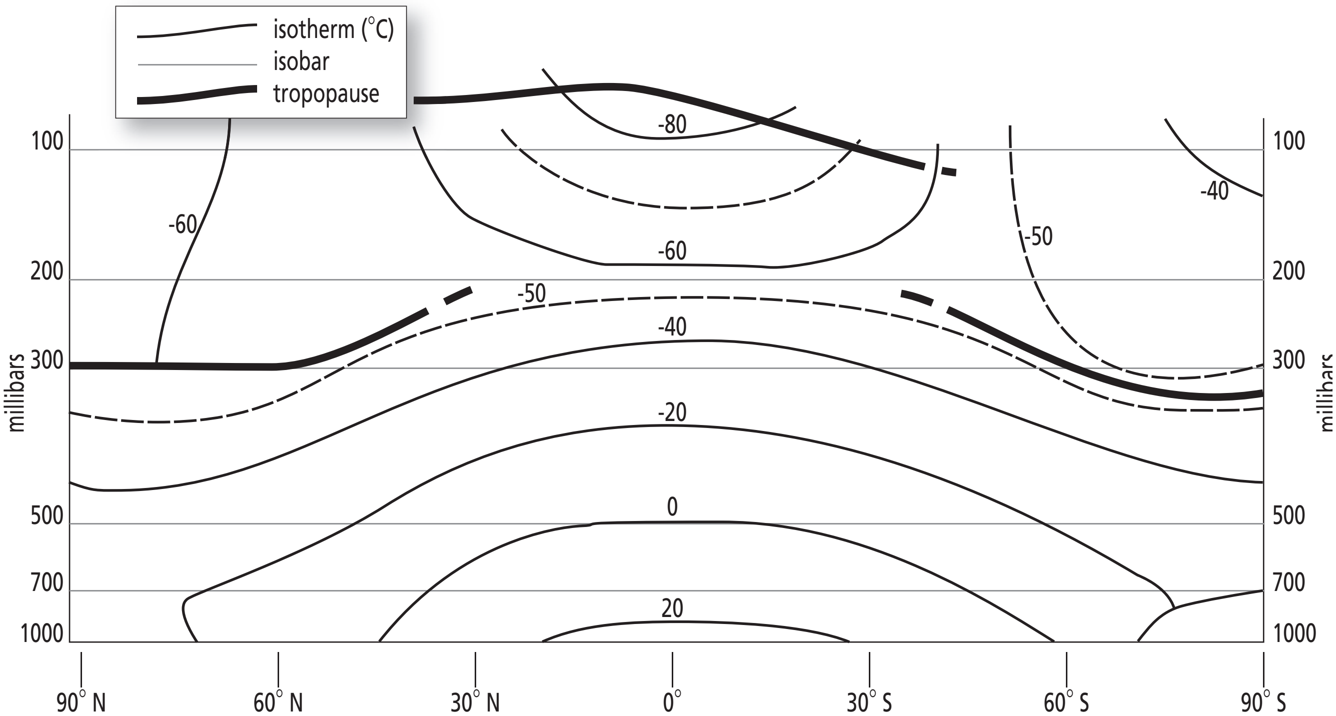
ball lightning A luminous sphere that is occasionally seen, often during a THUNDERSTORM. Most ball lightning spheres are 4–8 inches (10–20 cm) across, but they have also been reported as small as 0.5 inch (1.3 cm) and as large as 3 feet (1 m). They are most commonly red, orange, or yellow, and rather less bright than a 100-watt lamp.

The spheres move horizontally, quite slowly, sometimes pausing and remaining still for a few seconds. Some appear to spin and some bounce off objects and off the ground. Most seem to give off a pungent smell, like OZONE or burning sulfur. Although people who have been close to them report no sensation of heat, ball lightning has been known to scorch or burn wood and to make water boil when the sphere entered it. A few appearances have lasted longer than one minute, but most disappear after about 15 seconds, either fading away and vanishing or ending with a loud bang.

Several attempts have been made to explain ball lightning. The most plausible explanation is probably the one proposed in February 2000 by John Abrahamson and James Dinniss of the University of Canterbury, New Zealand. They suggested that when lightning strikes soil particles of silicon, silicon compounds are heated to about 3,000 K (5,924°F or 3,273°C) and thrown into the air. They then slowly oxidize, releasing their stored energy as heat and light.

Further Reading

Abrahamson, John, and James Dinniss. "Ball lightning caused by oxidation of nanoparticle networks from normal lightning strikes on soil." *Nature,* 403, 519–521.



A cross section of the atmosphere from pole to pole, showing how the isotherms (isopycnals would follow the same curves) cross the isobars in middle latitudes, producing a baroclinic atmosphere. In the Tropics, the isotherms and isobars are more nearly parallel and the atmosphere is barotropic.

Beaty, Bill. "Ball Lightning Page." Available online. URL: www.amasci.com/tesla/ballgtn.html. Accessed February 13, 2006.

Hubler, Graham K. "Fluff balls of fire." *Nature,* 403, 487–488.

baroclinic An adjective that describes the very common condition of an atmosphere in which surfaces of constant pressure (constant-pressure surfaces, also known as isobaric surfaces) and constant air DENSITY (isopycnic surfaces) intersect. The result is that the air density changes along each isobar (*see* ISO-). Baroclinicity is the state of being baroclinic.

Because the density of the air is related to its temperature, changes in density along the isobars means that there are steep horizontal temperature gradients in a baroclinic atmosphere. These gradients produce strong THERMAL WINDS.

In middle latitudes the atmosphere is usually strongly baroclinic. This explains the formation of FRONTS and JET STREAMS and the weather associated with them. A cross section of the atmosphere from pole to pole shows that the isopycnals or isotherms (*see* ISO-) are nearly parallel to the isobars in the TROPICS, where the atmosphere is BAROTROPIC, but cross them in middle latitudes.

A change in the flow of air can result in an increase in the baroclinicity. This is known as a baroclinic disturbance or baroclinic wave. It occurs when a barotropic flow is diverted, for example, by having to travel around a mountain. Air then begins to flow across the isotherms (the flow becomes baroclinic). This movement transports energy by ADVECTION, as cold air is carried into a region of warmer air and warm air is carried into a region of cooler air.

Any large disturbance to the barotropic flow produces a wave pattern in the flow of air. Baroclinic instability then causes the waves to grow in amplitude (*see* WAVE CHARACTERISTICS) and there are also changes in wind speed, because the air is accelerated as the flow becomes anticyclonic (*see* ANTICYCLONE) and decelerated when it becomes cyclonic (*see* CYCLONE). Although the disturbance begins by affecting the horizontal movement of air, it quickly generates vertical movements. These arise because cold air sinks as it moves into a warmer region and warm air rises as it moves into a cooler region.

Baroclinic instability in the middle and upper troposphere (*see* ATMOSPHERIC STRUCTURE) is associated with the waves of a frontal cyclone (*see* FRONTOGENESIS). If the change of wind speed with height (WIND SHEAR) exceeds about 3 feet per second for every 3,000 feet (1 m/s/km), waves with unstable wavelengths develop in the front at these heights and their wavelengths increase as the wind shear increases. Wind shear is linked to the temperature gradient, so this type of instability is said to be baroclinic.

A baroclinic field is a distribution of AIR PRESSURE and the mass of a given volume of air such that the density of the air is not a function only of atmospheric pressure.

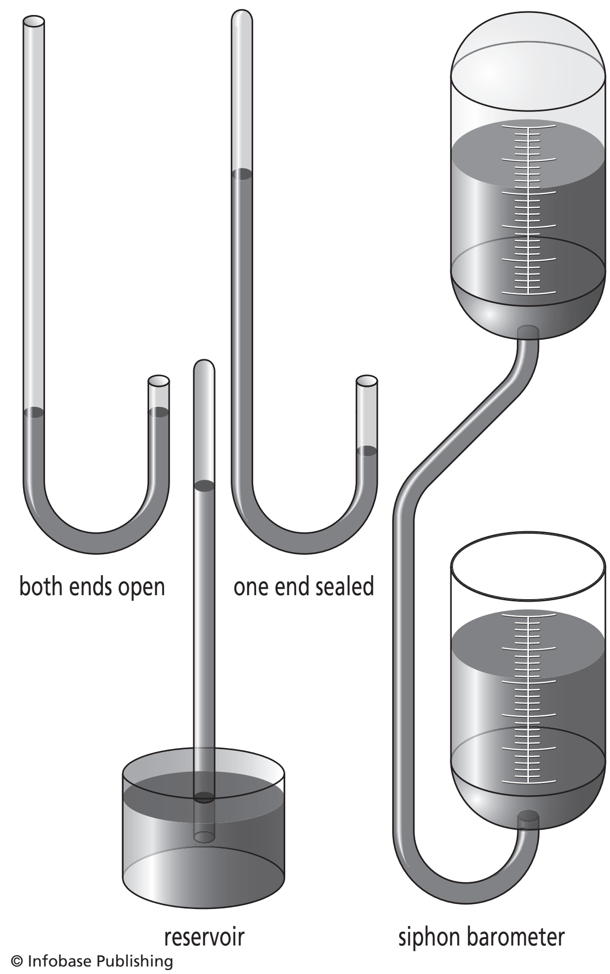
barometer An instrument that is used to measure AIR PRESSURE. Barometers are able to measure air pressure reliably because of the barometric law, which states that the air pressure balances the weight of all the air above the area being considered.

There are four general types of barometer: the mercurial barometer, aneroid barometer, hypsometer (hypsometric barometer), and piezoresistive barometer. All barometers measure the pressure that is exerted by the weight of the atmosphere on a unit area of surface (square inch or square centimeter). A barometer, in particular a household one that is mounted on the wall, is sometimes informally known as a weather glass.

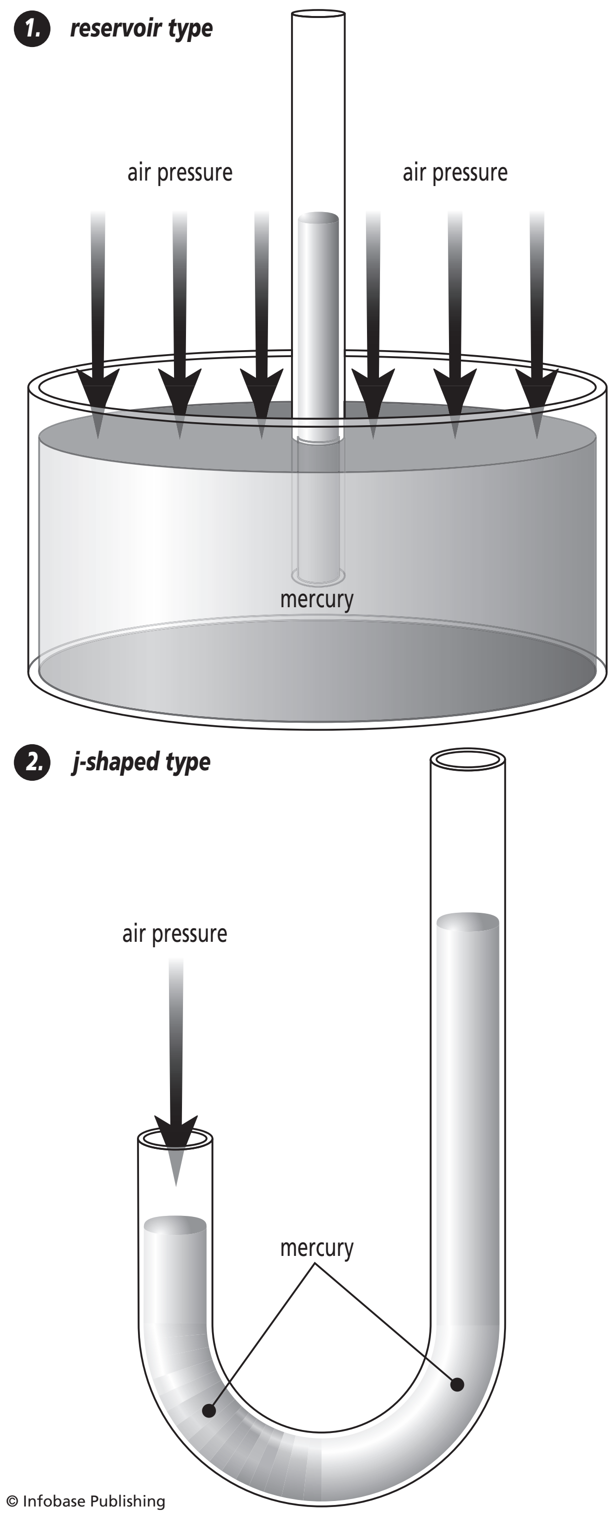
A mercurial barometer measures atmospheric pressure as the weight of a column of air that presses down on the exposed surface of mercury. A glass tube that is sealed at one end is filled with mercury. The tube is then inverted and supported vertically so its open end is below the surface of the mercury held in a reservoir. The weight of the atmosphere above the exposed surface pushes the mercury some distance into the tube. At standard sea-level pressure (*see* UNITS OF MEASUREMENT: standard atmosphere) the height of the column of mercury in the tube is 29.92 inches (760 mm). In an alternative design, the mercury is contained in a J-shaped tube and there is no reservoir. The taller arm of the tube is sealed and the end of the shorter arm is open to the air. Pressure is read from the difference in the height of the two columns of mercury.

Pressure (*P*) is calculated from the difference in height between the surface of the mercury in the reservoir and the mercury in the tube. This height difference (*h*) is multiplied by the density of mercury (*d*) and by the gravitational acceleration (*g*) acting on the mercury, so $P = hdg$. The density of mercury is 13.45 ounces per cubic foot (13.5 kg m^3) and *g* is 32.15 feet per second per second (9.8 m s^{-2}). If the mercury column is 29.92 inches (76 cm) tall, the air pressure will be 14.7 pounds per square inch or 1,013.25 hPa or 1,013.25 millibars.

This is the type of barometer that was invented in 1643 by Evangelista Torricelli (*see* APPENDIX I: BIO-



The simplest type of barometer comprises a reservoir containing mercury in which a tube stands upright. The reservoir can be dispensed with by using a U-shaped tube. If both ends of the tube are open, the mercury is at the same height in both arms of the U. If one end of the tube is sealed and there is a vacuum above the mercury, the mercury rises higher in the sealed arm than in the open arm. Pressure is calculated from the difference in the heights of the mercury in the two arms. The siphon barometer is a type of U-tube barometer.



In the reservoir type of mercury barometer, the end of an evacuated glass tube is inserted into a reservoir of mercury. Air pressure forces mercury up the tube. In the J-shaped type, there is no reservoir. Pressure is measured by the distance mercury is pushed up the longer arm of the tube.

graphical Entries). His barometer consisted of an open-topped reservoir of mercury and a narrow tube that was sealed at one end and open at the other. He filled the tube with mercury, placed his finger over the open end to seal it, inverted the tube in the reservoir so it was upright, then removed his finger. The mercury in the tube fell, but the tube did not empty because the pressure exerted by the weight of the atmosphere on the open surface of the reservoir pushed mercury some distance into the tube. The upper end of the tube, above the level of the mercury, contained a vacuum (in fact it contains a small amount of mercury vapor that evaporates into it, but the effect is too small to be of importance).

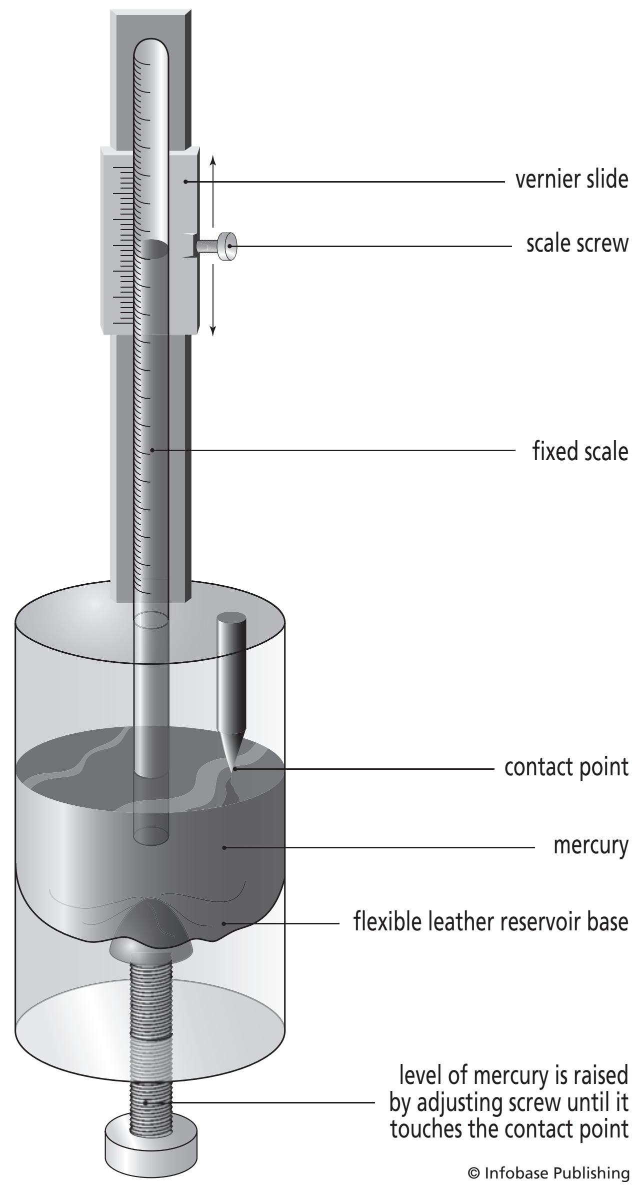
It is possible to dispense with the reservoir by using a U-shaped tube instead. If a tube that is open at both ends is partly filled with mercury, the level of mercury in the two sides of the U will be the same. If one end is sealed, however, the mercury in the side with the open end will act as the reservoir. The air pressure can then be calculated from the difference in heights of the two mercury columns.

There are several variations of the mercurial barometer. The siphon barometer is a U-shaped tube in which the two sides of the U are of unequal length. To make the instrument easier to read, the ends of the tube are much wider than the central part that connects them, and to save space the ends of the tube are arranged one directly above the other. The end of the shorter side is open and that of the longer side is sealed, with a vacuum above the mercury. The enlarged ends of both sides of the tube are calibrated and the pressure is calculated from the difference in the mercury level in the two sides of the tube.

A version of the siphon barometer is used to measure very small changes in air pressure. It uses a second liquid that is much less dense than mercury. Both liquids are held in the same U-shaped tube, but the part of one side of the tube that holds the lighter liquid is narrower than the part holding the mercury. A change in the level of the mercury produces a much bigger change in the level of the lighter liquid.

The disadvantage of all these types is that the air pressure cannot be read directly, because it depends on the difference between two levels of liquid. The problem is overcome in one type of siphon barometer, which has a flexible leather bag at the bottom of the open of the tube and a screw that presses upon it. By adjusting the screw, and thus the thickness of the bag, the height of the mercury in the open tube can be moved to a zero point. Then the height of the mercury in the closed end of the tube will always represent the difference in the two heights and it can be calibrated to read pressure directly. The Fortin and Kew barometers also avoid the complication of measuring the difference in heights.

The Fortin barometer is a portable mercurial barometer that was invented in 1800 by the French instrument maker Jean-Nicholas Fortin (1750–1831). It overcomes the difficulty with all mercurial barometers that the air pressure must be calculated from the difference between the level of the mercury in the barometer tube and the level in the reservoir. Fortin achieved this by making the bottom of the reservoir from flexible leather that can be raised or lowered by means of an adjusting screw. Before a reading is taken, the height of the mercury in the reservoir is raised or lowered until it just makes contact with a point fixed to the top of the reservoir. This places the level of the mercury in the reservoir in a predetermined position, so no further account need be taken of it. In the tube there is a vernier slide that can be moved by means of a screw on the side of the tube. The slide is lowered until its base just touches the top of the mercury and a reading is then taken against the fixed scale on the tube. To prepare the barometer for a journey, the adjusting screw is used to push the base of the reservoir upward until both it and the tube are filled with mercury.



The upper part of a Fortin barometer comprises the tube, fixed scale, vernier slide, and the screw for adjusting the slide. The lower part comprises the reservoir, the point against which the mercury is set, and the adjusting screw.

The length of the fixed scale varies from one instrument to another, depending on the locations in which it is to be used. Its upper limit must be extended if the barometer is to be used in a mine, for example, where the pressure is greater than it is at sea level.

The Fortin design makes no allowance for changes in temperature, which affect the volume of the mercury. It is also subject to errors due to CAPILLARITY, to the fact that the vacuum above the mercury is not complete, to small errors in the scales on the tube and vernier slide, and to errors in setting the instrument and in taking the reading. Despite these drawbacks, the Fortin barometer is sufficiently accurate for most purposes, and its ease of use and portability make it a very useful and popular type of barometer.

The Kew barometer is a type of mercurial barometer that allows the air pressure to be read directly from a scale at the top of its tube and no adjustment needs to be made to the level of mercury in its reservoir. It is based on the principle that if both the reservoir and the tube above it are perfectly cylindrical but of different diameters, then a change in the level of mercury in the reservoir will be a definite fraction of the change in the level in the tube. The central part of the tube is usually narrower than the remainder of the tube.

Kew barometers are often used at sea, because they can be made in such a way as to minimize the oscilla-

A Kew barometer, measuring the ordinary temperature range and calibrated in millibars and millimeters of mercury. ***(Casella CEL Ltd.)***

tion in the height of the mercury caused by the movement of a ship. Oscillation, or pumping, of the mercury level makes it impractical to use other types of mercurial barometers at sea.

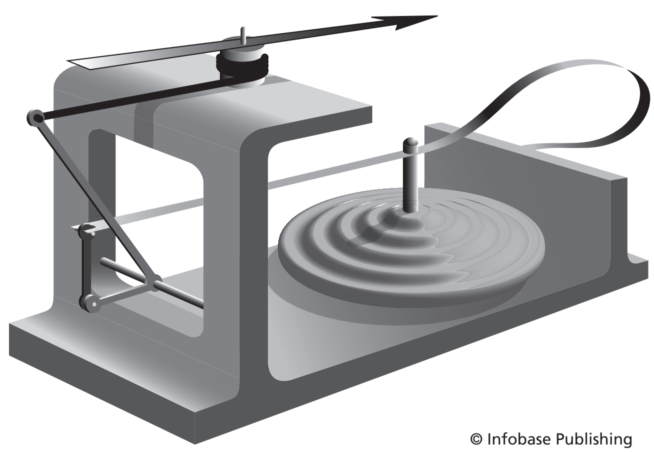
Kew barometers can also be transported. They are tilted until mercury fills the tube, then inverted and carried with the reservoir at the top. They can also be carried horizontally.

The aneroid barometer measures the effect of air pressure on a small metal box from which most of the air has been removed. The box is corrugated and acts like a bellows. It partly collapses when the air pressure increases, but a spring inside the box prevents it from collapsing completely. When the pressure decreases, the box expands. The position of the surface of the box may be measured electrically, but in most aneroid barometers the surface is linked to a spring and the spring to levers that move the needle on a dial.

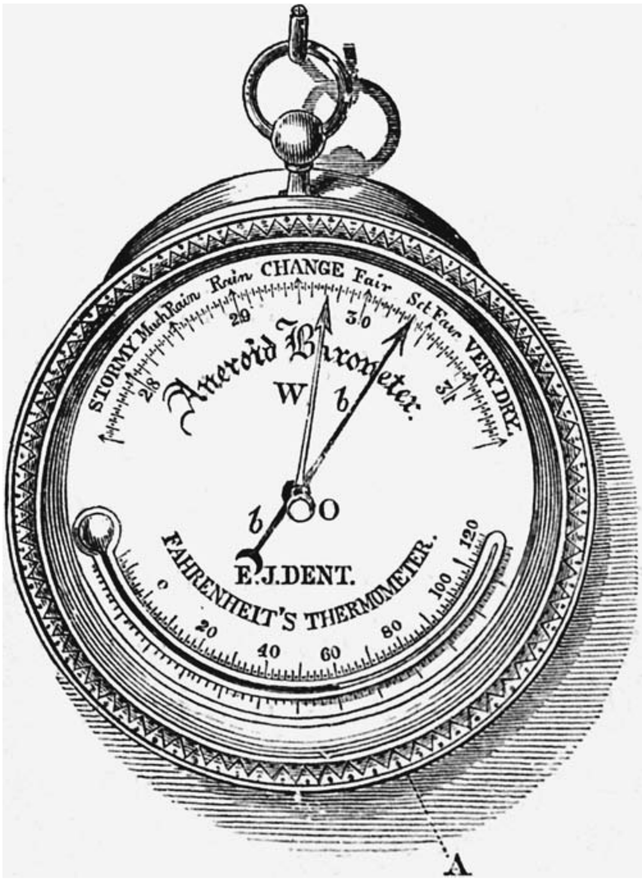
Aneroid barometers are less accurate than mercurial barometers, but because they do not contain a reservoir of mercury they are more convenient to use. Most barometers that people hang on the walls of their homes are of the aneroid type. Their dials are often labeled change, rain, much rain, stormy, fair, set fair, and very dry. These annotations were introduced in the 17th century by Robert Hooke (*see* Appendix I: Biographical Entries). Pressure altimeters and barographs are modified aneroid barometers.

A barograph also called an aneroidograph is an instrument that makes a continuous record of atmospheric pressure. It consists of a stack of partially evacuated boxes of the type used in aneroid barometers. Instead of being linked to a needle on a dial, however, the surface of the boxes is linked to a pen that can move in the vertical plane. The pen inscribes a trace on a paper chart, graduated to show pressure vertically and time horizontally, that is wrapped around a rotating drum. The drum turns at a constant rate, so the chart records the changes in pressure over time. The chart of changing atmospheric pressure it produces is known as a barogram.

A barograph that is designed to record very small changes in atmospheric pressure is known as a microbarograph. Microbarographs are used when it is necessary to record pressure changes very accurately.



In an aneroid barometer, the corrugated metal box expands and contracts with changes in air pressure. Movements of its surface are transferred by a spring and levers to a needle that moves on a dial.



The dial of an aneroid barometer, from *A treatise on the aneroid, an newly invented portable barometer,* by Edward J. Dent (1790–1853), published in 1849.

The hypsometer also known as the hypsometric barometer calculates air pressure by measuring the temperature at which a liquid boils. This is possible because the SATURATION VAPOR PRESSURE of a boiling liquid is equal to the atmospheric pressure acting on the surface of the liquid. The saturation vapor pressure of distilled water at 212°F (100°C) is 14.7 pounds per square inch (1,013.25 millibars), at 122°F (50°C) it is 1.79 pounds per square inch (123.45 mb), and at 77°F (25°C) it is 0.46 pounds per square inch (31.69 mb). Consequently, if the air pressure is 1.79 pounds per square inch (123.45 mb), distilled water will boil at 122°F.

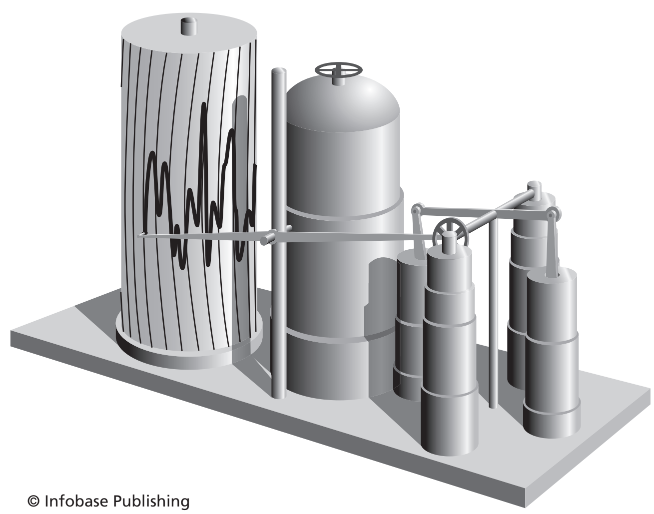
The hypsometer supplies heat to boil liquid that is contained in its reservoir and measures the temperature immediately above the liquid surface. Hypsometers are used to measure pressure at high altitudes, where other types of barometer are less accurate. At very high altitudes, where the pressure is 0.03–0.7 pounds per square inch (0.02–0.5 mb), carbon disulfide (CS_2) is sometimes used instead of water, because at sea-level pressure CS_2 boils at 114.8°F (46°C).

The piezoresistance barometer is based on elements that measure electrical resistance. Two of these are mounted at right angles to one another on the surface of a very thin silicon membrane. As changes in air pressure stretch the membrane, the resistance also changes. Barometers of this type are accurate, as well as small, light, and robust, which makes them convenient to carry and to use on vehicles and radiosondes. They are also inexpensive.

A fiducial point is a position that is fixed and from which other positions can be measured. The word *fiducial* is from the Latin verb *fidere,* which means "to trust." The fiducial point of a barometer, also called the standard temperature, is the temperature at which a particular barometer at latitude 45° gives a correct reading. At any other temperature or latitude the barometer reading must be adjusted. The fixed point that marks zero on the scale of a Fortin barometer is also called the fiducial point.

Actual pressure is the pressure recorded by a barometer after it has been corrected for temperature, latitude, and any instrumental error, but before the reading has been reduced to the mean sea level pressure.

Once the barometer reading has been corrected to bring it to a sea-level value, it is known as the reduced



A barograph is an aneroid barometer linked to a pen that makes a continuous trace on a chart attached to a rotating drum.

pressure. This reduction is necessary in order to make comparisons possible between the surface pressures at two places at different elevations.

At sea level the standard atmospheric pressure is 101.325 kPa (1013.25 mb, 29.92 inches of mercury). Pressure decreases with altitude, so when the sea-level pressure is 101.325 kPa the pressure at 5,000 feet (1,525 m) above sea level is 84.6 kPa and the pressure at 10,000 feet (3,000 m) is 70.1 kPa.

Barometric measurements taken at different elevations take no account of this effect. This makes comparisons complicated. Suppose there are two stations, A and B. A is 10,000 feet above sea level and B is 5,000 feet above sea level. Station A reports its pressure as 82.7 kPa, and station B reports 71.3 kPa. From these figures, and without adding a mention of the elevations of the two stations, it is not immediately obvious that the pressure at B is in fact higher than the pressure at A.

That is why all reported atmospheric pressures are corrected to their sea-level value. Sea level is used because, averaged over the year, its height is constant everywhere in the world (on shorter time-scales it varies locally because of TIDES, STORM SURGES, ocean currents (*see* APPENDIX IV: OCEAN CURRENTS), and variations in atmospheric pressure). No such obvious and uncontroversial datum can be found for locations on land. The barometric reading is corrected by applying the known relationship between pressure and elevation. This reduces the measurement to its sea-level equivalent.

The vertical distance between sea level and the zero level of the mercury in the reservoir of a barometer is called the barometer elevation.

Further Reading

National Physical Laboratory. "Frequently Asked Questions: How do I use a Fortin or Kew Pattern mercury barometer?" National Physical Laboratory. Available online. URL: www.npl.co.uk/pressure/faqs/usehgbaro.html. Accessed March 21, 2006.

barothermograph An instrument that records AIR PRESSURE and temperature simultaneously as a pen line on a chart fastened to a rotating drum. It is a combined barograph and THERMOGRAPH.

barothermohygrograph An instrument that records AIR PRESSURE, relative HUMIDITY, and TEMPERATURE simultaneously as a pen line on a chart fastened to a rotating drum. It is a combined barograph, hygrograph, and THERMOGRAPH.

barotropic An adjective that describes the condition of an atmosphere in which surfaces of constant pressure (constant-pressure surfaces, also known as isobaric surfaces) and constant air DENSITY (isopycnic surfaces) are approximately parallel at all heights. Horizontal temperature gradients are low, there is little or no change in wind direction or speed with height, and atmospheric conditions tend to be uniform over large areas.

A barotropic field is a distribution of AIR PRESSURE and the mass of a given volume of air, such that the density of the air is a function of only atmospheric pressure.

Horizontal WIND SHEAR can alter a barotropic atmosphere. Such an alteration is known as a barotropic disturbance or barotropic wave. It converts part of the KINETIC ENERGY in the wind shear into a wave that propagates through the atmosphere.

Beaufort wind scale The classification of winds according to their speed and effects that was devised in 1805 by Francis Beaufort, a British naval officer (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). The purpose of the scale was to instruct the commanders of warships as to the amount of sail their ships should carry in winds of different strengths. In 1838 the Beaufort scale was introduced throughout the Royal Navy and commanders were required to record wind conditions in their daily logs.

The International Meteorological Committee adopted the scale in 1874 for use in sending weather information by telegraph. For this purpose the scale was expanded to include brief descriptions of the state of the sea or of conditions on land.

In its original form the Beaufort scale made no direct reference to WIND SPEED. The 1831 version of Beaufort's original scale is set out in the table at the top of page 55.

The International Commission for Weather Telegraphers began in 1912 to calculate the wind speeds that would produce the effects described in the scale, but their work was interrupted by the outbreak of World War 1. It began again in 1921, when G. C. Simpson (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) was asked to undertake the task. His equivalent wind speeds were accepted in 1926. In 1939, the International Meteorological Committee standardized the scale by asserting that the wind speeds are based on values that would be registered by an ANEMOMETER set 20 feet (6 m) above the ground.

There are, therefore, two basic versions of the Beaufort scale. The first is the original one as Beaufort

Beaufort Wind Force Scale of 1831

Wind	Description	Sail
0. Calm		
1. Light air	Or just sufficient to give steerage way.	
2. Light breeze	Or that in which a man-of-war with	
3. Gentle breeze	all sail set, and clean full would go	
4. Moderate breeze	in smooth water from.	
5. Fresh breeze	Or that to which a well-	Royals, etc.
6. Strong breeze	conditioned man-of-war could just carry in chase, full and by.	Single-reefed topsails and just carry in chase, full and by. top-gallant sail.
7. Moderate gale		Double-reefed topsails, jib, etc.
8. Fresh gale		Treble-reefed topsails, etc.
9. Strong gale		Close-reefed topsails and courses.
10. Whole gale	Or that with which she could scarcely bear close-reefed main topsail and reefed foresail.	
11. Storm	Or that which would reduce her to storm staysails.	
12. Hurricane	Or that which no canvas could withstand.	

Beaufort Wind Scale

Force Speed MPH (km/h)	Name	Description
0. 0.1 (1.6) or less	Calm	Air feels still. Smoke rises vertically.
1. 1–3 (1.6–4.8)	Light air	Wind vanes and flags do not move, but rising smoke drifts.
2. 4–7 (6.4–11.2)	Light breeze	Drifting smoke indicates the wind direction.
3. 8–12 (12.8–19.3)	Gentle breeze	Leaves rustle, small twigs move, and flags made from lightweight material stir gently.
4. 13–18 (20.9–28.9)	Moderate breeze	Loose leaves and pieces of paper blow about.
5. 19–24 (30.5–38.6)	Fresh breeze	Small trees that are in full leaf sway in the wind.
6. 25–31 (40.2–49.8)	Strong breeze	It becomes difficult to use an open umbrella.
7. 32–38 (51.4–61.1)	Moderate gale	The wind exerts strong pressure on people walking into it.
8. 39–46 (62.7–74)	Fresh gale	Small twigs torn from trees.
9. 47–54 (75.6–86.8)	Strong gale	Chimneys are blown down. Slates and tiles are torn from roofs.
10. 55–63 (88.4–101.3)	Whole gale	Trees are broken or uprooted.
11. 64–75 (102.9–120.6)	Storm	Trees are uprooted and blown some distance. Cars are overturned.
12. more than 75 (120.6)	Hurricane	Devastation is widespread. Buildings are destroyed and many trees are uprooted.

prepared it. The second, set out above, is the one that is used today and that refers to conditions on land. The modern version was subsequently extended by the addition of categories to describe hurricanes (*see* SAFFIR-SIMPSON HURRICANE SCALE).

The Northern Rocky Mountain wind scale (NRM wind scale) is a scale of wind strength that has been adapted by the U.S. Forest Service for use in the forests of the northern Rocky Mountains. The forces and wind speeds are identical to those in the Beaufort wind scale, but the visible effects described for winds of each force are those likely to be seen in that region.

Beer's law A law stating that when light passes through a medium, the amount of light that is absorbed and scattered varies according to the composition of the medium and the length of the path traveled by the light. The law assumes the medium to be homogeneous and the light to be of a particular wavelength (*see* WAVE CHARACTERISTICS), but the law holds fairly well for the absorption and scattering of light traveling through the atmosphere and for the depth to which light penetrates water, snow, and ice. The law can be expressed as

$$K_z = K_0 e^{-az}$$

where K_z is the amount of light (K) reaching a depth z, K_0 is the amount of light at the top of the medium (in the case of the atmosphere, the SOLAR CONSTANT), e is the base of natural logarithms (2.718) and a is the amount of radiation that is absorbed per meter (known as the extinction coefficient).

beetle analysis The use of the remains of beetles to infer past climatic conditions. The wing cases (elytra) of beetles are often preserved in the soil. The species can often be identified from the elytra and the elytra can be dated (*see* RADIOCARBON DATING).

The technique is possible because many species of beetles live only where the temperature remains within certain, fairly broad limits and beetles respond more rapidly than plants to changes in temperature. The temperature range each species tolerates is known from studies of living beetles belonging to the same species. Where a number of such species occur together, all of their tolerable temperature ranges are compared. The temperature range in which all of them lived must be where the individual ranges overlap. This much narrower range is known as the mutual climatic range (MCR).

Bergen Geophysical Institute The institution that was founded in 1917 by Vilhelm Bjerknes (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) and his colleagues at Bergen, Norway. It had formerly been part of the Bergen Museum.

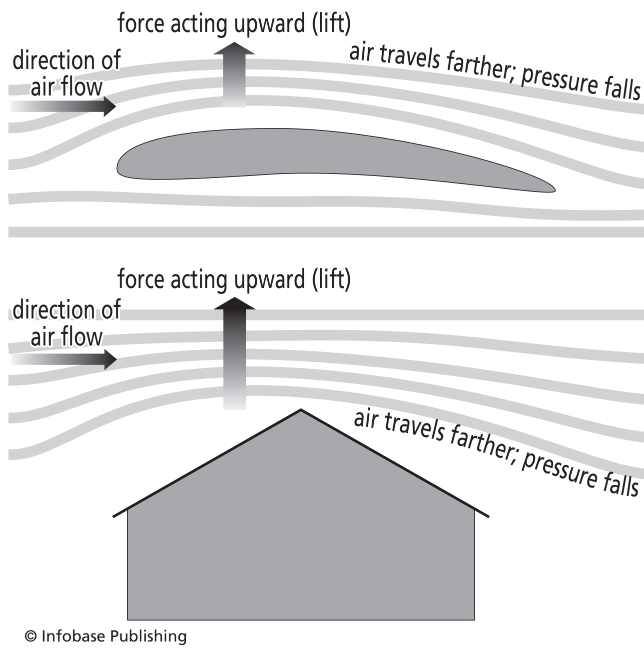
Bjerknes and his team of meteorologists developed the Institute as a center for meteorological research, and the ideas that were produced there in the 1920s and 1930s are often attributed to the Bergen School of meteorologists. These ideas included the theories of AIR MASSES and FRONTS. The Bergen Geophysical Institute is now part of the University of Bergen and specializes in meteorology and oceanography.

Bernoulli effect The reduction in air pressure that occurs when a wind blows across a convex surface, such as a ridged roof or the wing of an airplane, provided that the flow is laminar (*see* LAMINAR FLOW). This effect results from the Bernoulli principle discovered by Daniel Bernoulli (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), which states that the pressure within a fluid changes inversely with the speed of flow. The relationship can be expressed by:

$$p + 1/2\rho V^2 = \text{a constant}$$

where p is the pressure, ρ is the density of the fluid, and V is the velocity.

When air flows over a convex surface, it must travel farther than adjacent air that does not flow over the surface, but it must do so in the same time, because the STREAMLINES must rejoin on the other side of the



As the air passes over the upper surface of an airplane wing or a ridged roof, it must travel farther than the adjacent air. This accelerates the air and its pressure falls, generating an upward force (lift) on the wing or roof.

obstacle. This means that the air crossing the convex surface must accelerate. The air must also possess the same amount of energy when it has passed the obstruction as it had before encountering it. Consequently, since its velocity increases as it passes the convex surface, the only other form of internal energy it possesses, its pressure, must decrease. In the equation above, if V increases, p must decrease.

The Bernoulli effect explains why a strong wind can lift the roof from a building. It does so not by blowing from beneath the roof, but by reducing the pressure above the roof. Cyclists often experience the same effect. When a car passes a cyclist traveling fairly fast, the cyclist is drawn toward the car, not (as you might expect) pushed away from it.

Further Reading

Allaby, Michael. *Hurricanes*. Rev. ed. New York: Facts On File, 2003.

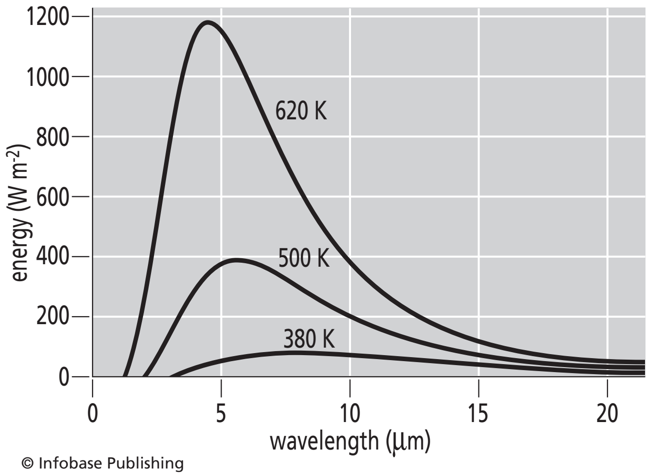
beta decay A type of RADIOACTIVE DECAY in which an unstable atomic nucleus changes into a nucleus with the same mass, but a different number of protons. There are two ways the decay can occur. A neutron may change into a proton with the emission of an electron and an antineutrino, or a proton may change into a neutron with the emission of a positron and a neutrino. Electrons and positrons (which are identical to electrons but carry a positive charge) emitted in this decay are known as beta particles and a stream of them is called beta radiation. This is the type of decay experienced by radioactive carbon-14. It is described by:

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + e^- + \bar{\nu}$$

Carbon-14 (^{14}C) has six protons ($_6C$). It changes into a nucleus with the same mass, but seven protons, which is nitrogen ($_7N$). The decay involves the emission of an electron (e^-) and an antineutrino ($\bar{\nu}$).

blackbody Any object (or body) that absorbs all of the radiant energy to which it is exposed and then radiates its acquired energy at the maximum rate possible for the TEMPERATURE it has reached is known as a blackbody. The energy radiated by a blackbody is known as blackbody radiation.

The concept of the blackbody grew out of the theoretical and experimental work of physicists in the 19th century. The Swiss physicist Pierre Prévost (1751–1839)



The graph indicates the energy emitted by blackbody radiation at different wavelengths.

demonstrated that heat is not a substance, and in 1791 Prévost pointed out that cold does not pass from snow to a person's hand, but heat flows from the hand to the snow.

In 1824, the French physicist Nicolas-Léonard Sadi Carnot (1796–1832) published a book called *Réflexions Sur la Puissance Motrice du Feu et Sur les Machines Propres à Développer Cette Puissance* (translated into English as *On the Motive Power of Fire*). In this work Carnot related the efficiency of an engine that burns fuel to the difference between the maximum and minimum temperatures in that engine. This work attracted much attention, stimulating research in thermodynamics (*see* THERMODYNAMICS, LAWS OF), which is the scientific study of the laws governing the conversion of energy from one form into another, the direction in which heat flows, and the ability of energy to perform work.

Balfour Stewart (1828–87), a Scottish physicist, developed the ideas of Prévost and Carnot. These led him to identify the properties of a blackbody. These were also discovered independently by his contemporary, the much more famous German physicist Gustav Robert Kirchhoff (1824–87), to whom the sole credit is often given.

The "body" is described as "black" because dark objects absorb energy and, in principle, a perfectly black body would absorb all the energy falling on it. This cannot happen in the real world, because it is impossible to make a body that reflects no electromagnetic radiation at all. Nevertheless, the theoretical concept proved extremely valuable, and Kirchhoff was able to explain its principle very simply by inviting us to suppose there is a box with blackened inside walls and only one tiny hole to provide access. Any radiation, of any wavelength (*see* WAVE CHARACTERISTICS), that enters the box through the hole will have only an infinitesimal chance of escaping again through the hole, so in effect it will have been absorbed. If the box is then heated until its interior is incandescent (until it glows), all wavelengths of light ought to emerge from the hole.

The Earth is not a perfect blackbody because some of the radiation falling on it is reflected (*see* ALBEDO), although the Sun is almost a perfect blackbody and the calculations based on the concept apply fairly precisely to both the Sun and Earth.

The relationships between the amount of energy absorbed by a blackbody and the amount emitted as blackbody radiation were discovered toward the end of the last century by the German physicist Wilhelm Wien (1864–1928) and the Austrian physicists Josef Stefan (1835–93) and Ludwig Boltzmann (1844–1906). They are now known as WIEN'S LAW and the STEFAN-BOLTZMANN LAW. If the wavelength at which a blackbody radiates most intensely is known, the surface temperature of the body can be calculated from Wien's law. If the surface temperature is known, the amount of energy it radiates can be calculated from the Stefan–Boltzmann law.

Using Wien's law, the temperature at the visible surface (photosphere) of the Sun is 6000 K (*see* TEMPERATURE SCALES). From this, the Stefan–Boltzmann law reveals that the Sun emits approximately 73.5 watts of energy from every square meter (W/m^2) of its photosphere. Multiplying this by the area of the photosphere shows that the total energy output of the Sun amounts to about 4.2×10^{20} MW. That is 420 billion billion million watts. This is a very large number, but if the Sun has continued for the entire 4.6 billion years since it formed to emit radiation at this rate by converting matter into energy according to Einstein's equation $E = mc^2$, it will have consumed only one-thousandth of its mass.

Only a minute proportion of this energy falls upon the Earth. The Sun radiates in all directions, and the Earth is a long way away and very small compared to its star. The amount of radiant energy reaching any object is inversely proportional to the square of the distance between that object and the source of the energy—in this case about 93 million miles (150 million km). This means that Earth intercepts no more than 0.0005 percent of the solar output. The actual amount of solar energy that arrives at the top of the Earth's atmosphere is known as the SOLAR CONSTANT.

A curve on a graph that shows the amount and wavelength of energy that is emitted by a blackbody at a particular temperature is known as a blackbody radiation curve. The graph shows radiation curves for several temperatures so they can be compared. Each curve is plotted by using Wien's law and the Stefan–Boltzmann law.

The blackbody radiation that is emitted by the surface of the Earth is called terrestrial radiation. It is approximately equal to the radiation emitted by a blackbody at a temperature of 255 K (-0.67°F, -18.15°C). Terrestrial radiation consists of infrared radiation in the waveband 4–100 μm (*see* SOLAR SPECTRUM), with a strong peak at a wavelength of about 12 μm, which is consistent with Wien's law.

blizzard A wind that is accompanied by heavy snow and a low air temperature. The NATIONAL WEATHER SERVICE defines a blizzard as a wind of at least 35 MPH (56 km/h), a temperature not above 20°F (-7°C), and snow that is either falling heavily enough to produce a layer at least 10 inches (250 mm) deep or that has been blown up from the surface and that reduces visibility to less than ¼ mile (400 m). In some areas the temperature requirement has been dropped.

Blizzards are extremely dangerous. Falling snow and snow lying on the ground combine to produce WHITEOUT conditions that are disorienting, and the cold wind has a strong WINDCHILL effect. When the temperature is 20°F (-7°C) in a 35-MPH (56-km/h) wind, windchill removes body heat at a rate equivalent to that of a temperature in still air of -20°F (-29°C).

Blizzards can occur anywhere. In February 1983, 47 people died in blizzards near Alayh, Lebanon. What were probably the worst blizzards to strike the United States in modern times occurred in 1888 and 1993. The 1888 blizzards lasted from January 11–13 and were triggered by a COLD WAVE. They affected Montana, North and South Dakota, and Minnesota. Then, from March 11–13 they struck the eastern states from Chesapeake Bay northward to Maine, with winds gusting to 70 MPH (113 km/h) and temperatures close to 0°F

(-18°C). The East River froze in New York, and snowdrifts almost 30 feet (9 m) deep lay in Herald Square, Manhattan. Fires could not be controlled, because fire engines could not reach them and tens of thousands of birds were killed by being frozen solidly to trees. More than 400 people died. The 1993 blizzards, lasting from March 12–15, affected the whole of eastern North America, killing an estimated 270 people in the United States and four in Canada. On January 22–23, 2005, what came to be known as the Blizzard of 2005 struck the northeast eastern United States and eastern Canada. By January 27, Logan International Airport, at Boston, Massachusetts, had recorded 43.1 inches (1.1 m) of snow, making January the snowiest month on record. On November 27–28, 2005, blizzards in parts of Nebraska and the Dakotas brought up to 20 inches (48 cm) of snow, and in South Dakota the storms brought down 8,000 utility poles and 10,000 miles (16,000 km) of transmission lines.

blocking The situation in which a particular type of weather persists for much longer than is usual, because the movement of air that would ordinarily bring a change in the weather is obstructed or diverted. Blocking occurs in middle latitudes, and it can last for a month or more, although it usually lasts for about two weeks. It happens most often on the eastern side of the North Atlantic, rather less often on the eastern side of the North Pacific, and also over the Kara Sea, to the east of Novaya Zemlya off northern Siberia, and near Baffin Island, in northern Canada. In the Southern Hemisphere, blocking most often occurs near New Zealand, but also over the southern Indian Ocean and to the southeast of South America. In the Northern Hemisphere blocking is most common in winter and spring. In the Southern Hemisphere it most often occurs in winter and summer.

In the middle latitudes of both hemispheres the prevailing winds are from the west and most weather systems move from west to east. They are drawn in this direction by the polar front JET STREAM, which also blows from west to east in both hemispheres. From time to time waves develop along the track of the jet stream. They grow more extreme until the jet stream breaks down for a time, after which it resumes its approximately straight path until more waves develop. This sequence of events is called the index cycle (*see* ZONAL INDEX).

Changes in the jet stream affect the weather systems below it. In the final phase of the index cycle ANTICYCLONES and CYCLONES become detached from the prevailing westerly AIRSTREAM. The process of detachment is called cutting-off. This usually happens in the upper troposphere (*see* ATMOSPHERIC STRUCTURE). The detached anticyclones and cyclones are known as cutoff highs and cutoff lows, respectively, and they are very slow-moving. Cutoff highs, also known as blocking highs, are usually centered between latitudes 50° and 70° in either hemisphere. Often, there are also cutoff lows, to either side of the blocking highs and to the south of them.

While this situation lasts, the jet stream, together with the weather systems associated with it, flow around each blocking high on the side nearest to the pole. Sometimes the jet stream divides, with one branch diverted to the north of the blocking high and the other to the south.

Air circulates anticyclonically (clockwise in the Northern Hemisphere) around a blocking high. Consequently, it draws warm air from a lower latitude into a higher one. This makes the core of the anticyclone warm. The lows, on the other hand, draw cool air into a lower latitude. The effect on the weather is more complicated, however.

Frontal systems (*see* FRONT), with changes in temperature that are associated with the passing of fronts, together with PRECIPITATION and storms, slow down as they approach the blocking high and are then diverted around it, following the path of the jet stream. Places to the north and south of the block are likely to experience more frontal weather than usual, but precipitation is much reduced in the area covered by the block and temperatures remain constant day after day.

Inside the blocking high and close to it, the weather is drier and warmer than is usual for the time of year. Blocking is believed to have been responsible for the severe DROUGHTS that affected the Great Plains in the 1890s and 1930s, and it caused a drought in northwestern Europe that lasted from May 1975 to August 1976. To the west of the high, where the circulation brings air from a lower latitude, the weather is unseasonally warm. On the eastern side, where the same circulation draws air from a higher latitude, the weather is unusually cold. The extreme warm or cold weather lasts for as long as the blocking high remains in position.

Although blocking is well understood, it remains very difficult to predict. Scientists hope that more detailed information about changes in sea-surface temperatures will allow them to identify the conditions that trigger it before blocks develop. Of course, prediction can do nothing to protect people against the difficulties that blocking sometimes causes.

blood rain Rain that is red because it contains red dust particles that have been transported from a distant desert region. After it has fallen, exposed surfaces are left covered by a thin layer of the dust.

Saharan dust often colors rain that falls in southern Europe and occasionally causes falls of blood rain as far north as Finland. Dust from the Australian desert has been known to fall as blood rain in New Zealand.

blowdown (**windthrow**) The breaking, uprooting, and blowing down of trees during a windstorm (*see* STORM). Evergreen trees are more likely to be blown down than deciduous trees. This is because windstorms occur more often in winter than in summer and in winter deciduous trees have shed their leaves and, therefore, offer less resistance to the wind than do evergreen trees.

Conifers (except for the larches) are evergreen, whereas most of the broad-leaved trees that grow in the middle latitudes where windstorms are most frequent are deciduous. Consequently, conifers are more likely to be blown down than broad-leaved trees. Conifers also tend to grow, and to be grown in plantations, on more exposed sites than broad-leaved trees. Broad-leaved trees can be blown down, of course, big, old trees with full crowns being more vulnerable than smaller trees, especially when they are in full leaf.

When forest trees fall they often bring down others and they expose still more trees, so groups of trees often fall, leaving a gap in the forest. Blowdown that is caused by prevailing winds (*see* WIND SYSTEMS), known in Britain as endemic windthrow, can be anticipated and its effects in plantations minimized by the pattern of planting. Rare events cannot be predicted, however. These can prove devastating and are known in Britain as catastrophic windthrows.

boiling The change of PHASE that occurs when a liquid becomes a gas, absorbing LATENT HEAT to supply the energy required for the change. In the liquid phase, molecules form small groups that are constantly breaking and rejoining and that can slide easily past one another. At the surface of the liquid, even when it is cold, molecules are constantly escaping into the BOUNDARY LAYER of air immediately above the surface and molecules in the boundary layer are returning to the liquid. The application of an increasing amount of heat causes the molecules in the liquid to move faster, the motion that is measured as the TEMPERATURE of the liquid, and a greater number of molecules are able to escape into the boundary layer.

The molecules in the boundary layer exert a VAPOR pressure, and when the SATURATION VAPOR PRESSURE is reached, molecules begin to escape from the boundary layer and into the air above it. If sufficient heat is applied to the liquid, groups of molecules will break apart below the surface, forming bubbles of vapor (not air) that rise to the surface because the vapor is less dense than the liquid. This is boiling.

In order for molecules to escape from the boundary layer, the vapor pressure they exert must exceed the atmospheric pressure. When the amount of heat applied to the liquid has raised its temperature to a level at which the vapor pressure exceeds the atmospheric pressure, the liquid will boil. Consequently, the temperature at which a liquid boils varies according to the AIR PRESSURE. At sea-level pressure of 1,013.25 millibars (mb), pure water boils at 212°F (100°C). At any pressure below 6.11 mb, water that is exposed to the air cannot remain in the liquid phase, because its boiling temperature is below its freezing temperature, which also varies with pressure. At a pressure of 6.11 mb and a temperature of 32.018°F (0.01°C), water exists simultaneously in all three of its phases: as liquid, with some ice floating on its surface, and water vapor

Boiling Temperature °F	°C	Atmospheric Pressure (mb)
392	200	15,536
320	160	6,176.8
248	120	1,984.9
212	*100*	*1,013.25*
140	60	199.33
68	20	23.38
32	0	6.11

above the surface. This is known as the triple point for water. The table gives the boiling temperature of water at a range of pressures, with the figures for sea-level pressure in italic.

bolometer An instrument that is used to measure radiant energy. It was invented by S. P. Langley (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) in 1880 and it works by measuring the rise in temperature of a blackened metal strip that is placed in one of the arms of a Wheatstone resistance bridge.

A Wheatstone resistance bridge compares the electrical resistance in an object placed in one of its arms with the resistance of another arm, which is known. The change in temperature alters the electrical resistance in the strip. When linked to a galvanometer (an instrument that measures small electric currents), the deflection of the galvanometer needle is proportional to the intensity of the radiation.

Modern bolometers use a metal strip that consists of strips of platinum made into four gratings. A bolometer can measure a temperature difference of 0.0018°F (0.0001°C). The distribution of the intensity of radiation through the spectrum is measured by a spectrum bolometer. This has a single metal strip set on its edge in one arm of a resistance bridge.

bottom water The water that lies in the deepest part of the ocean. It is denser than water near the surface, and at a constant temperature of 34–36°F (1–2°C) in all oceans. The water flows very slowly and is driven by variations in density (*see* THERMOHALINE CIRCULATION).

boundary current An ocean current (*see* APPENDIX VI: OCEAN CURRENTS) that flows close to the coast of a continent and parallel to it. Boundary currents flow in either a northerly or southerly direction and are caused by the deflection of an east–west or west–east current where it meets the continental landmass.

Ocean boundary currents strengthen as they flow along the western margins of the oceans. This is known as western intensification. The currents become narrower and faster as a result of the combined action of internal friction, WIND stress, and VORTICITY. They move northward in the Northern Hemisphere and southward in the Southern Hemisphere. Currents along the eastern margins of the oceans are broader and slower.

The boundary currents on the western sides of oceans in both hemispheres are deep, narrow, fast-flowing, and carry warm water. These currents are most prominent in the Atlantic and Pacific Oceans, as the Gulf Stream in the North Atlantic, the Kuroshio Current in the North Pacific, the Brazil Current in the South Atlantic, and the Agulhas Current in the South Pacific.

The currents on the eastern sides of the oceans are wide, shallow, slow, and carry cool water. These are the Canaries Current in the North Atlantic, the California Current in the North Pacific, the Benguela Current in the South Atlantic, and the Peru Current in the South Pacific. Currents in the Indian Ocean are more complicated.

boundary layer The layer of air that lies immediately adjacent to a surface and within which atmospheric conditions are strongly influenced by the proximity of the surface. A boundary layer may be very thin. The boundary layer above a water surface in which water molecules are constantly being exchanged with the liquid is about 0.04 inch (1 mm) deep. Other boundary layers are deeper. The PLANETARY BOUNDARY LAYER extends from the surface to an average height of 1,700 feet (519 m).

The layer of air that is in direct contact with a surface and in which air molecules are able to move only slowly due to VISCOSITY, is called the laminar boundary layer. Flow in this layer is laminar (*see* LAMINAR FLOW) and parallel to the surface.

The WATER VAPOR in the boundary layer of air that is in contact with an exposed surface of liquid water is called equilibrium vapor. The water vapor is in equilibrium because its amount does not change. Water molecules are constantly leaving the liquid surface by EVAPORATION, but molecules are returning to the liquid by CONDENSATION at the same rate. If the number of molecules leaving the liquid increases, the number returning to the liquid will also increase by the same amount. If molecules leave the layer by moving into the air above the layer, they will be replaced immediately by molecules escaping from the liquid, but in this case the volume of the liquid will be decreased. If the loss continues, the water will diminish by evaporation.

Bowen ratio The ratio of sensible heat (*see* ENTHALPY) to LATENT HEAT, which indicates how energy is apportioned at the Earth's surface. Solar energy is absorbed at the surface and is used to evaporate (*E*) water. Evaporation absorbs latent heat of vaporization (*L*) and some of the remaining energy is released from the surface as sensible heat (*H*)—heat that warms objects exposed to it. The temperature and water-vapor content of the air at two levels above the surface can be measured, and from this the ratio (β) can be calculated as: $\beta = H/LE$.

Most surfaces tend to keep the ratio at a minimum. If β is greater than 1, more energy is being released into the atmosphere as heat than is being used for evaporation.

Brückner cycle A cyclical change in the weather that occurs over a period of about 35 years. The English scientist Francis Bacon (1561–1626) was the first person to suggest the existence of a 35-year weather cycle, shortly before he died in 1626, but in 1890 the German geographer and glaciologist Eduard Brückner (*see* Appendix I: Biographical Entries) produced clear evidence for it. He based this on his detailed examination of weather records over many years.

Brückner found that the temperature and precipitation in Europe vary over a period of 34.8 ± 0.7 years. Each cycle consists of a cool, moist half and a warm, dry half. In the course of each cycle the temperature varies by not more than 2°F (1.1°C) and the rainfall varies by 8–9 percent. The amplitude of the wave (*see* wave characteristics) is small, but clearly recognizable when plotted on a graph. Modern climatologists consider the Brückner cycle to be of only minor importance in determining weather patterns.

Brunt-Väisälä frequency The frequency with which an atmospheric gravity wave (*see* atmospheric wave) oscillates. If a parcel of air is displaced upward, it will sink again, overshooting and rising several times in a wave pattern about its level of neutral buoyancy. The frequency of this oscillation is the Brunt-Väisälä frequency and it is given by $N/2\pi$, where $N = [(g/\theta)/\partial\theta/\partial z0]^{½}$, where g is the gravitational acceleration, θ is the constant potential temperature of the parcel of air, and $\partial\theta/\partial z$ is the vertical gradient of potential temperature.

Buchan spells Periods in the year when the usual rise or fall of temperature with the seasons is halted or reversed. There are often a few days, or even a week or two, when the weather becomes colder in spring or warmer in the fall and people describe the weather as "unseasonal." The Scottish meteorologist Alexander Buchan (*see* Appendix I: Biographical Entries) suspected these periods might occur as a regular feature of the climate.

To investigate this possibility, in 1869 Buchan examined the temperature records for Edinburgh from 1857 to 1866. He discovered that cold departures from the temperature trend occurred from February 7–14, April 11–14, May 9–14, and June 29 to July 4. The warmest weather was in July. After that, as the average temperature fell, there were warm periods from August 6–11, November 6–13, and December 3–14. It was popularly assumed that Buchan had found regular fluctuations that applied quite generally and could be anticipated. This is how they came to be called "Buchan spells." In fact Buchan claimed no such thing. He made it clear that the periods he identified varied from year to year and that they applied only to southeastern Scotland. Similar spells of unseasonal weather do occur in most places, but their dates vary. They are now known as singularities.

Budyko classification A climate classification, known as the radiational index of dryness, that was proposed in 1956 by M. I. Budyko (*see* Appendix I: Biographical Entries). It is based on the net radiation that is available for the evaporation of water from a wet surface (R_o) and the heat that would be required to evaporate the whole of the mean annual precipitation (Lr), where r is the latent heat of vaporization. The ratio of these two values is used to designate climate types. The drier the climate the larger is the ratio and unity (a ratio of 1.0) marks the boundary between dry and moist climates. The climate types used in the scheme are listed in the table.

R_o/Lr	Climate Type
greater than 3.0	desert
2.0–3.0	semi-desert
1.0–2.0	steppe grassland
0.33–1.0	forest
less than 0.33	tundra

buoyancy The upward force that is exerted on a body when it is immersed in a fluid. Archimedes' principle states that when a body is immersed in a fluid it displaces its own volume of the fluid. This reduces the weight of the body by the weight of the displaced fluid. That is why bodies weigh less in water than they do in air and why very large animals, such as whales and hippopotamuses, are able to move freely and gracefully through water.

If the weight of the body is greater than the weight of its own volume of the fluid, the body will sink through the fluid. It will then experience negative buoyancy. If the body weighs less than the displaced fluid, it will experience positive buoyancy. This acts as an upward force, and the body will rise. If the weight of the body is equal to the weight of the displaced fluid, the body will experience neutral buoyancy and will neither sink nor rise.

The weight of a body is determined by its volume and its DENSITY—its weight per unit volume. Consequently, the buoyancy that a body experiences when immersed in a fluid depends on the density of the body compared with the density of the fluid. Despite their vast bulk, the density of the bodies of whales and hippopotamuses is very close to the density of water (approximately 0.6 ounce per cubic inch, 1 g/cm^3), but much greater than the density of air (at sea level 0.008 ounce per cubic inch, 0.01 g/cm^3). Consequently, these large animals experience neutral or only slightly negative buoyancy in water, but strongly negative buoyancy in air.

Buoyancy occurs in air when a PARCEL OF AIR has a different density from the air surrounding it. This can be expressed as:

$$F/M = g[(\rho' - \rho)/\rho]$$

where F is the buoyancy force, M is the mass of the air parcel, g is gravitational acceleration, ρ' is the density of the surrounding air, and ρ is the density of the parcel of air. Dividing F by M gives the buoyancy force per unit of mass and $(\rho' - \rho)/\rho$ is the buoyancy, often designated by B. The force exerted by the buoyancy is therefore the buoyancy (B) multiplied by the gravitational acceleration (g), or gB.

The generation of vertical air motion by buoyancy forces and the rise of warm air are called development. Development leads to a direct circulation (*see* FRONT).

The physical principle that is used to calculate the buoyancy of any body that is immersed in a fluid is known as Archimedes' principle. It was discovered by the Greek mathematician and inventor Archimedes (*c.* 287–212 B.C.E.) while he was seeking the solution to a puzzle presented to him by King Hieron II of Syracuse.

Archimedes was a native of Syracuse, a city in Sicily. He belonged to an aristocratic family and was a personal friend, and possibly a relation, of King Hieron.

According to the traditional story, Hieron had ordered a new crown from a local goldsmith, specifying that it was to be made of the purest gold. When the crown was delivered, Hieron began to suspect that although it was golden in color, the metal was alloyed with silver. Silver was less costly than gold, but the king had paid for gold and so, if his suspicion was correct, he had been cheated. Hieron asked Archimedes to determine whether or not the crown was made from pure gold. There was one condition: Archimedes must not damage the crown in any way.

Archimedes pondered this for some time. Then, one day as he was stepping into his bath, some of the water overflowed onto the floor. He realized that his foot and leg had displaced their own volume of water and this gave him a way to solve the problem of the crown. He was so delighted that he ran naked down the street shouting "eureka, eureka" ("I've found it, I've found it").

He borrowed from a trustworthy goldsmith a piece of pure gold of precisely the same weight as the crown. He immersed the pure gold in water, marking on the side of the vessel the height to which the water rose when he did so. Then he repeated the procedure with the crown and found that the water rose a little higher. Silver weighs less than gold, so the volume of a given weight of an alloy of silver and gold is greater than the volume of the same weight of pure gold. Archimedes had proved that the crown was not made from pure gold. According to the story, Hieron had the dishonest goldsmith executed.

butterfly effect A metaphor that was invented by the American meteorologist Edward Lorenz (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) to illustrate what is known formally as "sensitive dependence on initial conditions." On December 29, 1979, Lorenz presented a paper in Washington, D.C., at the annual meeting of the American Association for the Advancement of Science that had the title "Predictability: Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?"

Lorenz was then a research scientist at the Massachusetts Institute of Technology. While developing mathematical computer models of weather systems he found that weather patterns repeated themselves, but each time with differences that arose from extremely small variations in their starting conditions. Two apparently identical weather systems could develop entirely differently if one of their initial parameters differed by one part in a thousand—one millibar of pressure, for instance, or a small fraction of a degree in temperature. This showed that weather is unpredictable for more than a few hours ahead and that changes in a weather system may be caused by factors arising within the system itself. Lorenz's work led to the development of the mathematical theory of CHAOS and had a strong influence on meteorological research.

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Buys Ballot's law The rule stating that in the Northern Hemisphere, if you stand with your back to the wind there is an area of low pressure on your left. In the Southern Hemisphere, if you stand with your back to the wind the area of low pressure is on your right.

The American meteorologist William Ferrel deduced this law in 1857 on theoretical grounds and a few months later the Dutch meteorologist C. H. D. Buys Ballot (*see* APPENDIX I: BIOGRAPHICAL ENTRIES, for details of both scientists) announced his discovery of it based on records of the wind circulation around midlatitude CYCLONES. When Buys Ballot learned of Ferrel's work, he immediately conceded precedence and the rule should perhaps be known as Ferrel's law. Unfortunately, Buys Ballot was too late and his name had already been firmly attached to the discovery, and it has been known as Buys Ballot's law ever since.

Expressed a little more technically, the law states that the wind blows at 90° to the direction of the PRESSURE GRADIENT, due to the balance between the PRESSURE GRADIENT FORCE and the CORIOLIS EFFECT. This is true of the GEOSTROPHIC WIND in the free atmosphere (the atmosphere above the PLANETARY BOUNDARY LAYER). It is not strictly true of the wind that blows in the planetary boundary layer, where the wind is affected by FRICTION and the angle between the wind and the pressure gradient is less than 90°.

The law does not apply close to the equator, where the Coriolis effect is extremely small or, at the equator itself, does not exist.

C

CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) A joint US–French satellite that was scheduled to be launched early in 2006. During its development, CALIPSO was known as PICASSO–CENA (Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations—Climatologie Etendue des Nuages et des Aerosols). On December 16, 2005, CALIPSO and CloudSat were prepared to be launched together on a Delta II rocket as soon as a launch date was confirmed.

CALIPSO will be commanded and monitored from a center in France, and its data will be transmitted to the NASA Langley Research Center at Hampton, Virginia. The two satellites will be in a Sun-synchronous polar ORBIT at a height of 438 miles (705 km). They will measure AEROSOL and cloud properties, radiative fluxes, and the state of the atmosphere, thus providing high-vertical resolution profiles of the radiative effects of aerosols and clouds that will help in studies of climate change.

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calm belt One of the regions in which the winds are usually weak and the air is often still. These regions extend as latitudinal belts around the Earth. The calm belts occur in the horse latitudes (*see* WEATHER TERMS). These are close to the TROPICS and so they are sometimes known as the calms of Cancer and the calms of Capricorn.

Calymmian A period of geologic time during the Mesoproterozoic era that lasted from about 1,600 million years ago until 1,400 million years ago. BACTERIA and cyanobacteria were the only forms of life. *See* APPENDIX V: GEOLOGIC TIMESCALE.

Cambrian The period of geologic time that lasted from 542 million years ago until 488.3 million years ago. It is the period in which the first animals with mineral skeletons appeared. *See* APPENDIX V: GEOLOGIC TIMESCALE.

capacitance A property of electrical conductors that allows them to store electric charge. The concept is most commonly applied to systems of conductors or semiconductors separated by insulators. Capacitance is measured in farads (*see* UNITS OF MEASUREMENT).

Cape Hatteras low A deep DEPRESSION that forms from time to time over the North Atlantic, off Cape Hatteras, North Carolina, and then moves northward. It brings strong northeasterly winds and storms to coastal areas from Virginia to the Maritime

Provinces, often with flooding and damage to property. The storms are known as nor'easters (*see* LOCAL WINDS) and are most frequent between September and April.

capillarity The process by which water moves upward through a very narrow space, such as a tube or the spaces between soil particles. It occurs because the water molecule is polar (*see* POLAR MOLECULE) and it is the way water rises through unsaturated soil from the GROUNDWATER to within reach of plant roots.

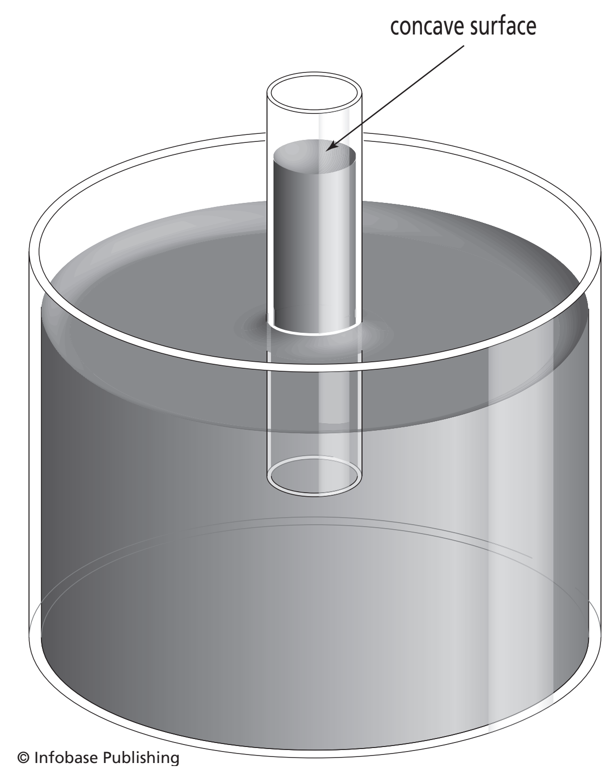
Suppose that a narrow glass tube, open at both ends, is inserted vertically into a vessel containing water. One end of those molecules that are in contact with the sides of the tube is attracted to the opposite electric charge of molecules in the walls of the tube. This attraction draws the water molecules upward, along the sides of the tube. The rising water molecules are linked by hydrogen bonds (*see* CHEMICAL BONDS) to the molecules behind and to the sides of them, and these are drawn behind the rising molecules. The liquid is drawn upward only at the sides of the tube, however, so the water at the sides rises higher than the water at the center. This causes the surface of the water in the tube to sag at the center, forming a concave shape.

SURFACE TENSION acts on the molecules at the surface of the water in the tube, pulling them toward the configuration that requires the least energy to maintain. This is a sphere, so surface tension seeks to make the surface resemble a sphere by pushing it upward at the center, into a convex (bulging) shape. More of the molecules close to the sides of the tube are then exposed to the attraction of opposite charges, so they move a little farther up the sides, drawing more molecules behind them. They leave the center behind, so it resumes its concave shape, which surface tension seeks to correct. In this way the water moves up the tube.

As soon as the surface of the water in the tube is higher than the surface of the water in the vessel, gravitational force will act to restore them both to the same level. Water will continue to rise up the tube for as long as the attractive force between the water molecules and the sides of the tube is stronger than the gravitational force. When the two are equal the water will cease to rise.

It follows from this that the distance water will rise by capillarity depends on the width of the space. Wider spaces hold more water and, therefore, the column of water is heavier and the point at which the weight of the water column is equal to the attractive force is reached at a lower level. If the tube is wide, the weight of water in it exceeds the attractive force before the water is able to rise at all.

With even the narrowest tube, there is a limit to the height water will rise by capillarity. This is the height at which the pressures acting on the water are in balance. In the vessel, from which the water is rising, the pressure exerted by the water is greater at the bottom than at the top, because of the weight of the overlying water. The water pressure decreases from the bottom to the top of the vessel, and at the surface it is zero, because there is no water bearing down upon it. The water pressure continues to decrease with height in the capillary tube, but since it decreases from zero at the surface of the water in the vessel its value above the surface, in the tube, must be negative. The opposite of a pressure (pushing) is a tension (pulling) and in soils this is called soil moisture tension.



Water is drawn up the narrow tube by the attraction between water molecules and the side of the tube and between the water molecules themselves.

Carbon Reservoirs

Reservoir	Billion Tons	Billion Tonnes
Geological reservoir		
Carbonate rocks	109,820	99,839
Fossil fuels	44,000	40,000
Methane hydrates	88,000	80,000
Ocean reservoir		
Ocean	41,800	38,000
Land reservoir		
Soils	1,650	1,500
Living organisms	550	500
Atmospheric reservoir		
Atmosphere	803	730
Total	110,000,000	100,000,000

The limit of capillarity is the height at which the negative value of the soil moisture tension is the same as the positive value of the water pressure at the bottom of the vessel. At this point the two are in equilibrium. In soil, therefore, the depth of the groundwater determines the height to which water can be drawn by capillarity.

carbon cycle The movement of the element carbon through the atmosphere, living organisms, soil, rocks, and water. Carbon enters the atmosphere initially in the form of CARBON DIOXIDE (CO_2) that is released from volcanoes. The table lists the approximate amount of carbon that is held in each of these reservoirs.

Methane hydrates (mentioned in the table at left) are methane (CH_4) that is held inside the crystal structure of ice. This methane is found in sedimentary rocks, mainly beneath the sea floor but also in some places on land.

In the course of the carbon cycle, carbon moves between the reservoirs. Each year approximately 232.21 billion tons (210.85 billion tonnes) moves through the cycle. The table lists the sources that release carbon and the sinks that absorb it.

The nuclei of all carbon atoms contain six protons, but they contain a varying number of neutrons. The number of neutrons affects the mass of the nucleus, but not its chemical behavior, which is determined only by its protons. The sum of the number of protons and neutrons (nucleons) is called the nucleon number (or mass number) and is the way isotopes are labeled. There are seven carbon isotopes: ^{10}C, ^{11}C, ^{12}C, ^{13}C, ^{14}C, ^{15}C, and ^{16}C. The isotopes ^{12}C and ^{13}C are stable. The other isotopes are radioactive. Their HALF-LIVES are: ^{10}C 19.1 seconds; ^{11}C 20.4 minutes; ^{14}C 5,720 years (*see* RADIOCARBON DATING); ^{15}C 2.4 seconds; and ^{16}C 0.74 second.

Some atmospheric CO_2 dissolves in cloud droplets and falls to the surface as weak carbonic acid (H_2CO_3), and CO_2 also dissolves directly into surface waters. In water, H_2CO_3 dissociates into hydrogen (H^+) and bicarbonate (HCO_3^-) ions. Bicarbonate then dissociates further into carbonate (CO_3^{2-}) ions. These combine with positively charged ions, such as calcium (Ca^{2+}) to form salts, in this case calcium carbonate ($CaCO_3$), which is insoluble in shallow water.

At ocean depths below about 2.5 miles (4 km), the low temperature of the water and the fact that the water is saturated with CO_2 cause $CaCO_3$ to dissolve.

Annual Carbon Cycle

Source	Amount (billion tons; billion tonnes)	Sink	Amount (billion tons; billion tonnes)
Respiration	132; 120	Photosynthesis	132; 120
Oceans	99.66; 90.50	Oceans	99; 89.90
Volcanoes	0.11; 0.10	Burial as rock	0.22; 0.20
Weathering	0.22; 0.20	Weathering	0.22; 0.20
Decomposition in oceans	0.22; 0.20	Dissolved organic carbon from land	0.44; 0.40
		Fossilization	0.33; 0.30
Total	**232.21; 210.85**		**232.21; 210.85**

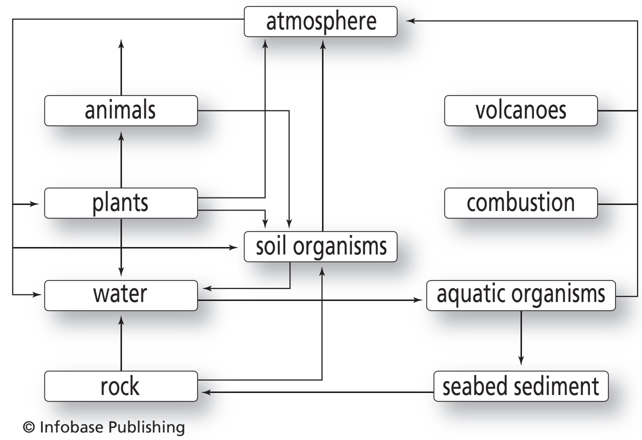
The depth at which this occurs is known as the carbonate compensation depth (CCD).

Certain aquatic organisms exploit this reaction to make the shells in which they live. When they die, the insoluble $CaCO_3$ shells sink to the seabed to form part of the seabed sediment. Eventually this is transformed into carbonate rock, such as limestone and chalk, as a result of pressure and heating due to movements of the Earth's crust. Some sedimentary rocks are subducted beneath the crust (*see* PLATE TECTONICS) and become the source of the carbon that returns to the atmosphere from volcanoes. Other sedimentary rocks become exposed to the air as a result of tectonic processes. They are then subjected to WEATHERING, in the course of which $CaCO_3$ is broken down and CO_2 is returned to the air.

Plants absorb CO_2 directly from the air and use it in the production of carbohydrates by the process of PHOTOSYNTHESIS. Animals obtain the dietary carbohydrates they need by eating plants, and carnivorous animals eat herbivorous animals. Animals and plants obtain the energy that their bodies need by the process of RESPIRATION, in which carbohydrates are oxidized. This reaction releases energy and the by-products of the respiration are water (H_2O) and CO_2, both of which are returned to the air.

A hierarchy of organisms decomposes dead plant and animal material. Each of these organisms utilizes compounds obtained from the decaying material to construct and repair their own tissues, and for respiration. By the time the soil organisms have completed the process of decomposition, all of the CO_2 that was absorbed during photosynthesis has been returned to the air by respiration.

At various times in the past decomposition has not been complete. Plant material fell into the soft, airless mud of tropical swamps, where it was buried and later compressed and heated to form coal. Some of the coal that is mined today consists of the remains of plants that grew during the Silurian Period, about 400 million years ago, but most lived about 350 million years ago, during the Carboniferous Period (*see* APPENDIX V: GEOLOGIC TIMESCALE). Other organic remains were buried by sediments in river deltas. The sediments became trapped between two layers of impermeable rock and were heated strongly under high pressure and in airless conditions. This "pressure cooking" converted them into petroleum and natural gas (mainly methane, CH_4).



Carbon moves through the air and is absorbed by plants. Plants and animals pass carbon to organisms living in soil and seabed sediments, and their respiration returns the carbon to the air.

Coal, gas, and petroleum are known as fossil fuels. The name refers partly to the fact that they were formed a very long time ago, but mainly because at one time anything that was dug from the ground was called a "fossil." The Latin *foss* means "dig."

Fossil fuels consist of carbon that has been removed from the air and stored. Burning the fuel involves oxidizing the carbon to CO_2 with the release of energy, and completing the process of decomposition. In this way the carbon is returned to the air. This is one way in which our activities are affecting the carbon cycle.

It is the principal but not the only way. Human activities also accelerate the weathering of carbonate rocks. Calcium oxide (CaO), or lime, is used in the chemical process industries and a suspension of calcium hydroxide ($Ca(OH)_2$), or slaked lime, in water is used to remove sulfur from the waste gases of industrial plants that burn fossil fuel, especially power plants, in order to combat ACID DEPOSITION. Calcium oxide is obtained by heating (called kilning) limestone. Heat breaks down calcium carbonate to produce lime (calcium oxide) and CO_2: $CaCO_3 + \text{heat} \rightarrow CaO + CO_2$. Lime is converted to slaked lime by the addition of water: $CaO + H_2O \rightarrow Ca(OH)_2$. Kilning limestone to obtain lime returns to the atmosphere the carbon dioxide that was removed from the air many millions of years ago, in the shells of aquatic organisms, and isolated from the atmosphere.

Almost all climate scientists agree that by adding CO_2 to the atmosphere human activities are altering the global climate (*see* GLOBAL WARMING and GREENHOUSE EFFECT). Every year, between about 7.15 billion tons (6.5 billion tonnes) of carbon are released into the atmosphere in the form of carbon dioxide as a result of burning fossil fuels. Cement manufacture, which involves kilning limestone, releases about 0.22 billion tons (0.20 billion tonnes). In addition, about 1.87 billion tons (1.7 billion tonnes) are released through changes in land use, especially in the TROPICS. This makes a total of 9.24 billion tons (8.4 billion tonnes).

Changes in land use also increase the capacity of certain sinks. Newly planted forests absorb carbon, as do improvements in farm productivity (because of higher yields of plant material). These changes remove about 2.09 billion tons (1.9 billion tonnes) of carbon from the air each year. The figure for the absorption of carbon due to changes in land use is an estimate, however, introduced to balance the cycle. Balancing is needed, because the amount of carbon being absorbed each year is smaller than the amount being emitted. Without this adjustment, 2.09 billion tons (1.9 billion tonnes) of carbon would remain unaccounted for. Until the adjustment was made, this was known as the missing carbon.

Overall, human activities release more carbon into the air than they remove from it. Consequently, the amount of atmospheric carbon dioxide is accumulating at a rate of about 3.52 billion tons (3.2 billion tonnes) each year. This rate of accumulation has remained unchanged since the 1980s. Scientists are unsure why the rate of accumulation does not increase in step with the rising rate of emissions. The most likely explanation is that plants grow more vigorously in an atmosphere enriched with CO_2. This is called the carbon dioxide fertilization effect.

carbon dioxide (CO_2) A gas that is formed by the complete oxidation of carbon (*see* CARBON MONOXIDE). Carbon dioxide is a minor constituent of the atmosphere, at present comprising 365 parts per million by volume (p.p.m.v.), or 0.0365 percent. It is the most important greenhouse gas (*see* GREENHOUSE EFFECT) and climatic changes in the past have been associated with changes in the atmospheric concentration of CO_2. Data from ICE CORES drilled at the VOSTOK STATION cover four transitions from ice ages (GLACIAL PERIODS) to warm periods that began about 335,000, 245,000, 135,000, and 18,000 years ago. In each case, the warming was associated with an increase in CO_2 concentration, from about 180 to 240–300 p.p.m.v. It is not certain, however, whether the rise in CO_2 concentration caused the warming or was a consequence of it. Some research suggests the last three warming episodes occurred 500–1,000 years before the rise in atmospheric CO_2.

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Carboniferous The period of geologic time (*see* APPENDIX V: GEOLOGIC TIMESCALE) that began 359.2 million years ago and ended 299 million years ago. North America, Europe, North Africa, Arabia, northern Australia, and part of northern China lay in the TROPICS during the Carboniferous and, especially in the latter part of the period, forests covered vast areas in these tropical continents. Fallen trees, tree branches, leaves, and other dead plant and animal material fell into swamps and marshlands, where they were buried by sediment before they had completely decomposed. Subsequent compression and heating converted this organic material into almost one-quarter of the world's coal measures.

American geologists divide the Carboniferous into two epochs. The Mississippian epoch, named in 1870 by the geologist Alexander Winchell (1824–91) for the limestone lying beneath coal-bearing rocks in the Mississippi valley, lasted from 359.2 million years ago until 318.1 million years ago.

The Pennsylvanian epoch, named in 1891 by the geologist Henry Shaler Williams (1847–1918), lasted from 318.1 million years ago until 299 million years ago. Williams identified the epoch by its coal-bearing rocks and named it for Pennsylvania, the state where these were best known.

carbon monoxide (CO) A gas that is formed by the partial oxidation of carbon (*see* CARBON DIOXIDE). Carbon monoxide is emitted naturally by volcanoes and forest fires, and by the incomplete combustion of fossil fuels (*see* CARBON CYCLE), especially in internal combustion engines.

The amount of carbon monoxide present in the air is very small, but it varies greatly, the highest concentrations occurring along busy main highways and city streets. When inhaled, carbon monoxide forms a stable compound with blood hemoglobin, reducing hemoglobin's capacity to transport oxygen, and in high doses carbon monoxide is lethal, although persons exposed to less than lethal doses recover fully.

Carbon monoxide is chemically stable. It oxidizes to carbon dioxide and dissolves in the oceans, but it is also utilized by soil micro-organisms and this is believed to be the route by which most of it is removed from the atmosphere.

carbon sequestration The long-term storage of the carbon dioxide (CO_2) that is produced by processing and burning fossil fuels (*see* CARBON CYCLE) in order to prevent it from accumulating in the atmosphere. Natural gas is primarily methane (CH_4), but when it first emerges from its natural reservoir the methane is often mixed with CO_2. Most customers will accept gas containing a maximum of 2.5 percent CO_2. Any CO_2 in excess of this proportion must be removed. Some of the gas produced in the North Sea contains up to 9 percent CO_2.

Norway imposes a CO_2 tax, set in January 2000 at $38 for every ton of CO_2 released into the atmosphere. This encouraged the owners of the Sleipner oil and gas field in the Norwegian sector of the North Sea to install equipment to compress the CO_2 that is separated from the CH_4 and to pump it under pressure into a sandstone formation beneath the seabed. Similar schemes are being developed at gas fields in other parts of the world, including the South China Sea and Barents Sea, as well as at the Alaskan oil fields.

Carbon dioxide from the burning of fuel can also be buried in this way, and there is a pilot gas-fired generating plant in Norway that pumps its CO_2 into underground reservoirs. CO_2 can be pumped into depleted oil or gas wells, coal beds that cannot be mined, salt domes that have been mined for their salt, and deep AQUIFERS which contain water that is too salty to be used. CO_2 can also be released directly into the sea, either frozen as DRY ICE (solid carbon dioxide) or from a pipeline that is towed behind a ship or that runs from the surface to the seabed.

There are disadvantages to carbon sequestration, however. The size of the total reservoir capacity—the volume of space available for storing carbon dioxide—is unknown, and probably it is only the power-generating industry that could adopt the technology economically. In particular, it might not be economically feasible to dispose of CO_2 emissions from mobile sources, such as vehicles and aircraft.

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carbon tetrachloride (tetrachloromethane, benziform, carbon chloride, methane tetrachloride, perchloromethane, CCl_4) A clear, volatile liquid that was once widely used as a solvent, especially in dry cleaning, in fire extinguishers, as a pesticide used to kill insects in stored grain, and in the industrial preparation of other compounds including CFCS. It is very toxic to humans if inhaled or swallowed and it also contributes to the enhanced GREENHOUSE EFFECT, having a global warming potential of about 1,550. It is also a source of free chlorine atoms that contribute to the depletion of stratospheric OZONE.

In the United States, the Occupational Safety and Health Administration (OSHA) sets a limit of 10 parts per million for carbon tetrachloride in workplace air for an eight-hour workday and 40-hour workweek. It was banned in consumer products in 1970.

Most carbon tetrachloride is produced by reacting carbon disulfide (CS_2) with chlorine (Cl_2): $CS_2 + 3Cl_2 \rightarrow CCl_4 + S_2Cl_2$.

At the fourth meeting of the signatories to the Montreal Protocol on Substances that Deplete the Ozone Layer (*see* APPENDIX V: LAWS, REGULATIONS, AND INTERNATIONAL AGREEMENTS) held in Copenhagen in November 1992, it was agreed that the use of carbon tetrachloride should cease by January 1996. Small amounts continue to be used, but carbon tetrachloride is no longer released into the atmosphere.

Cenozoic (Cainozoic, Kainozoic) The era of geologic time that began about 65.5 million years ago and that extends to the present day. It includes the PALEOGENE, NEOGENE, and PLEISTOGENE periods (*see* APPENDIX V: GEOLOGIC TIMESCALE).

The Cenozoic saw the evolution of mammals into the many species seen today, following the extinction of the dinosaurs at the end of the preceding CRETACEOUS period. Later, it is the era marked by the recurrence of GLACIAL PERIODS punctuated by INTERGLACIALS.

Central England climate record A continuous record of the mean monthly temperatures that have been experienced in central England since the year 1659 and a continuous record of daily temperatures in the same area since 1772. The record was published in 1974, having been compiled by Gordon Manley, Professor of Environmental Sciences at the University of Lancaster until he retired in 1967.

The area that is covered forms a triangle approximately with the cities Preston, Bristol, and London at its corners. Measurements taken since 1974 have been adjusted for the urban HEAT ISLAND effect. This is the longest continuous climate record, based on instrument readings, that exists anywhere in the world. The record is held and regularly updated at the Climate Data Monitoring section of the Hadley Centre of the United Kingdom METEOROLOGICAL OFFICE.

The record shows that the average temperature in central England rose by about 1.2°F (0.6°C) in the course of the 20th century, the warmest years being 1990 and 1999. The period from 1993 to 2002 was 1.26°F (0.7°C) warmer than the 1961–90 mean, making this the warmest in the entire record.

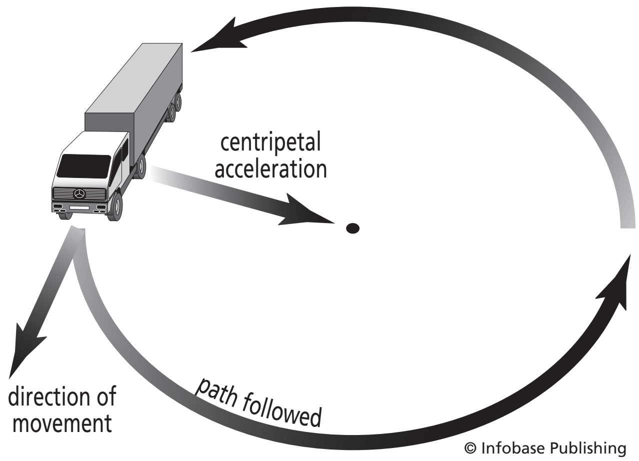
The record of temperatures from 1659 covers an area of England bounded by the cities of Bristol, Preston, and London.

centripetal acceleration The motion of a body that is following a curved path. Although the speed of the body may remain constant, its direction constantly changes. This means that it is accelerating, because ACCELERATION is defined as the rate of change of VELOCITY, and velocity is a VECTOR QUANTITY that comprises both speed and direction. If the speed decreases, the effect is nevertheless an acceleration, in this case a negative acceleration, although it is often called "deceleration" to avoid confusion.

According to Newton's first law of motion: A body will continue in a state of rest or uniform motion along a straight path unless an external force is applied to it. If such a force is applied, its effect will be to change either the speed at which the body is moving, or the direction in which it is moving, or both. This means it will change the velocity of the body, and, by definition, a change in velocity is an acceleration. Newton's second law states: The acceleration of a body is proportional to and in the same direction as the force acting on that body. It follows that if a body is moving along a curved path, a force must be acting on it to accelerate the body toward the center of the curve. This is centripetal acceleration. Its magnitude is equal to mv^2/r, where m is the mass of the body, v its velocity, and r the radius of curvature of its path.

If someone fastens a weight to the end of a string and swings it in a circle, the string will be taut and the weight will follow a curved path. A centripetal force acting along the string and toward the body of the person holding the string accelerates the weight toward the person. Should the string break, the weight will fly away, because once the centripetal force ceases to act, the weight reverts to its motion in a straight path, according to the first law.

Centripetal acceleration can be observed and measured only by an observer who is in an external frame of reference that is in a state of inertia with respect to the body moving in a curved path. An observer inside



As the truck follows its circular path, its motor propels it forward, at a tangent to the circle, but a countervailing force, exerted by the grip of its tires on the road surface, draws it toward the center of the circle. The two forces balance, allowing the truck to continue.

the rotating frame of reference experiences things differently. To the person swinging the weighted string, it *feels* as though the force is acting outward, not inward. A passenger riding in a car that is traveling fast around a tight corner feels as though a force were pushing away from the center of the turn. If there is a tennis ball lying on the flat shelf behind the rear seat, it will roll toward the outside of the turn. Fighter pilots flying at high speed in a tight turn or pulling out of a steep dive experience it as a force pressing them down into their seats and draining the blood from their heads so they may lose first color vision (gray out) and then all vision (black out). Their loss of vision is genuine. They are not imagining it. Sometimes people call this effect a centrifugal force. It is perfectly real, but it is not a force acting outward from the center of the turn.

An observer in an INERTIAL REFERENCE FRAME would see more clearly what is really happening. That person would see that the tennis ball in the car, like the weight that breaks free from the string, does not experience a centripetal acceleration. Consequently, the ball and the weight obey Newton's first law and move in a straight path, in fact at a tangent to the curved path. That is also what the bodies of passengers and fighter pilots are attempting to do. The pressures they experience are the combined effects of their inertia and their centripetal acceleration. The centrifugal force does not exist.

Moving air also experiences a form of centripetal acceleration known as lateral acceleration. This is the acceleration of air in a direction that is perpendicular to the wind direction and it happens when air is affected by the centripetal force as it flows around a center of high or low pressure. In order to maintain the centripetal acceleration the PRESSURE GRADIENT FORCE must exceed the CORIOLIS EFFECT, so there is a net acceleration at right angles to the direction of the GEOSTROPHIC WIND and the resulting wind is subgeostrophic.

CFCs (chlorofluorocarbons) CFCs are a range of chemical compounds in which chlorine and fluorine are bonded to carbon. Bromine and fluorine are bonded to carbon in a related series of compounds, with or without chlorine, and hydrogen is present in compounds known as HCFCs. METHYL CHLOROFORM (CH_3CCl_3) and CARBON TETRACHLORIDE (CCl_4) are also grouped with the CFCs because their atmospheric effects are similar. Chlorine, fluorine, and bromine are known chemically as halogens and these compounds are also called halocarbons.

CFCs were invented in the 1930s by scientists working for DuPont de Nemours and Company and were given the trade name "Freon." Their commercial value arose from their physical and chemical properties. CFCs change between the liquid and gaseous phases at about room temperature, which means that they can be used in freezers, refrigerators, and air conditioning units. In these applications they lower the temperature inside the unit by absorbing the latent heat of vaporization from the surrounding air as the liquid expands and vaporizes. The heat is released outside, where a compressor causes the gas to condense. The same property made them useful as propellants in aerosol cans. CFCs are liquid while held under moderate pressure; when the pressure is released they vaporize and expand, spraying vapor from the nozzle of the can and carrying droplets of any substance that is mixed with them. They were also used as solvents and foaming agents in foam plastics.

Other compounds could also be used for these purposes, but CFCs were chemically highly stable. This means they are very reluctant to react with other substances, which in turn means that they are nonflammable and completely nontoxic. The most likely alternatives to CFCs were ammonia, which can be used in refrigeration plants but is poisonous, and butane and propane, which are suitable propellants and foaming agents but are highly flammable. CFCs were very safe.

Their chemical stability also meant that once released into the air they would remain there for a long time before adhering to a solid surface and disappearing. In 1970, the Dutch chemist Paul Crutzen showed that the OZONE LAYER was vulnerable to destruction by chemical reactions, and in 1974 the American chemists F. Sherwood Rowland and Mario Molina warned that those reactions might involve CFCs. All three were awarded the 1995 Nobel Prize in chemistry for these findings (*see* APPENDIX I: BIOGRAPHICAL ENTRIES).

Because they are very stable, CFCs and other halocarbons survive long enough to enter the stratosphere. There they absorb ULTRAVIOLET RADIATION, which splits their molecules, releasing free atoms of chlorine. Chlorine atoms destroy ozone and atomic oxygen repeatedly by reactions that end by releasing the original chlorine atoms:

$$Cl + O_3 \rightarrow ClO + O_2$$

$$ClO + O \rightarrow Cl + O_2$$

Production and use of these halocarbons is now banned in many countries under the Montreal Protocol on Substances that Deplete the Ozone Layer (*see* APPENDIX V: LAWS, REGULATIONS, AND INTERNATIONAL AGREEMENTS).

The table below lists principal compounds with the number of years they survive in the atmosphere.

CFC and Related Compounds

Name	Formula	Atmospheric Residence Time (years)
CFC-12 (Freon-12)	CCl_2F_2	100
CFC-11 (Freon-11)	CCl_3F	45
CFC-113	CCl_2FCClF_2	85
methyl chloroform	CH_3CCl_3	4.8
carbon tetrachloride	CCl_4	35
H-1301	$CBrF_3$	65
H-1211	$CBrClF_2$	16
HCFC-22	$CHCl_2F$	12
HCFC-142b	CH_3CClF_2	19
HCFC-141b	CH_3CCl_2F	9

Chandler wobble A periodic change in the position of the Earth's axis of rotation and, therefore, of the location of the north and south geographic poles. The magnitude of the change is approximately 0.1 minutes of arc and its period—the time taken to complete the cycle and return to its initial position—is about 14 months.

The effect of the Chandler wobble is to alter all latitudes by that amount. This small change could produce much larger changes in the circulation of the atmosphere, with significant climatic effects.

The cause of the wobble is uncertain. It is believed to be due to changes in the angular MOMENTUM of the solid Earth and atmosphere, combined with the effect on electrically charged water droplets of changes in the magnetic field, and possibly the positions of other planets in the solar system. The wobble was predicted in 1744 by the Swiss mathematician Leonhard Euler (1707–83), who calculated the period as precisely one year. In about 1881, the American geophysicist Seth Carlo Chandler (1846–1913) studied the phenomenon using his own observations and by examining old records, especially those from the Greenwich observatory in England. He found that the actual period was about 14 months (428 ± 17 days). It is now known that the period of one year would be true if the Earth were completely rigid, but that the interior of the Earth is slightly elastic, and it is this that increases the period.

Channeled Scablands An area of about 13,000 square miles (33,670 km^2) between the valleys of the Columbia and Snake Rivers in Washington State, where the soil has been scoured from the surface and the land is dissected by deep canyons, called coulees. The coulees have steep, stepped sides and are approximately rectangular in cross section. Streams that flow through the coulees are much too small to have carved the canyons by erosion. The landscape is so harsh that scientists study it to help them understand the landscapes of Mars. In a series of papers in the *Journal of Geology,* the first of which was published in 1923, the American geologist J. Harlan Bretz proposed what is now the accepted explanation of how the landscape was formed.

During the most recent ice age, the Wisconsinian GLACIAL PERIOD, glaciers formed a succession of dams at the edge of the ICE SHEET. Water accumulated behind the dams until there was a lake, now

Channeled Scablands in Lake Roosevelt National Recreation Area, Washington ***(Lake Roosevelt National Recreation Area)***

called Lake Missoula, that had a surface area of about 3,000 square miles (7,770 km^2), in some places was 2,000 feet (610 m) deep, and that held 500 cubic miles (2,080 km^3) of water. About 15,000 years ago the climate warmed a little and the last of the dams broke. This released a wall of water 2,000 feet (610 m) high into the Clark and Flathead Rivers. The wave traveled at more than 50 MPH (80 km/h) and carried up to 10 cubic miles (42 km^3) of water an hour. The torrent filled the valleys, cut new channels, and fell in huge waterfalls that cut deep plunge pools.

The landscape still bears the scars of this catastrophic event caused by a change in the climate.

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chaos A mathematical theory that describes dynamic systems which are governed by nonlinear equations. A nonlinear equation is one of the type $y = x^2$ that does not produce a straight line when plotted on a graph. If $y = x^2$, a small change in the value of x will produce a very much bigger change in the value of y. Consequently, the development of a chaotic system through time is acutely sensitive to very small differences in the starting conditions. In the natural world such systems usually involve several equations each of which is much more complicated than the example given here. Because the sensitivity to the precise initial conditions is so acute, the behavior of the system is essentially unpredictable, because those initial conditions can never be known with sufficient accuracy. If the system is observed over time, it will appear to behave randomly—or chaotically. Systems that behave in this way are said to be complex.

In 1961, Edward Lorenz (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), a research meteorologist at the Massachusetts Institute of Technology, discovered that weather systems are complex in this sense. Computers model the atmosphere by constructing an imaginary three-dimensional grid, describing the state of the air at each intersection in the grid. When the model is run, an initial change in one part of the grid produces effects that ramify across the grid. These changes are calculated mathematically, in terms of pressure, temperature, and humidity, at each intersection of grid lines and the calculations are repeated in a series of steps. With even the finest grid, conditions between the grid lines have to be assumed, so inevitably the initial data are somewhat approximate. Since the weather system is complex, these small discrepancies magnify at each step in the calculation, making a weather forecast based on the model increasingly inaccurate the longer it is run. If the model is run twice, with even the smallest differences in the initial conditions, the weather it describes in one run soon becomes vastly different from that in the other run. Lorenz discovered this when he started a run using initial data the computer had generated part way through a previous run, but to save time he entered numbers to three decimal places rather than the six places stored in the computer memory. The second run should have duplicated the results of the first, but it diverged rapidly to describe an entirely different weather pattern.

This sensitive dependence on initial conditions came to be called the BUTTERFLY EFFECT: the notion that a butterfly flapping its wings in China can affect the way a storm develops a month later in America. It implied that weather forecasts can be reliable for no more than a few days in advance and, consequently, attempts at long-range weather forecasting was abandoned.

Despite being called chaotic, the behavior of complex systems is not random. Patterns emerge over time, offering the possibility that with better understanding prediction may become possible. In recent years, meteorologists have identified a number of cycles and oscillations that strongly influence the weather over large areas and allow very general predictions to be made, in some cases up to a year ahead.

Further Reading

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chaparral A type of shrubland that is found on dry hillsides and ridges from southern Oregon to Baja California, but that is most widespread in Shasta County, California, and the area to the south and on the western side of the Sierra Nevada. Chaparral also occurs in discontinuous belts across Arizona. Similar types of vegetation around the Mediterranean are known as maquis, macchia, or garrigue, in central Chile they are known as matorral, in southern Australia as mallee scrub, and on the southern tip of Africa as fynbos or cape scrub.

Most of the perennial plants are evergreen shrubs and small trees. Many of these are broad-leaved, with leaves that are small, tough, and leathery as an adaptation to dry conditions. The climate is strongly seasonal, with hot, dry summers and mild winters (*see* CLIMATE TYPES: Mediterranean climate). Rainfall is 12–36 inches (300–900 mm) a year, of which 65 percent falls between November and April in the Northern Hemisphere and between May and October in the Southern Hemisphere.

chemical bonds All chemical compounds are composed of molecules, which are atoms of elements that are joined together. The way that atoms link to form molecules is called bonding.

An element is a substance that cannot be broken down into simpler substances. The nuclei of all the atoms of an element contain the same number of protons—particles carrying a positive electromagnetic charge. It is the number of protons in its atomic nuclei that give an element its chemical properties, so any sample of a particular element will react chemically in exactly the same way as any other sample of that element. The atoms of an element may differ in the number of neutrons in their nuclei. Neutrons are particles that are slightly more massive than protons and that carry no electromagnetic charge.

Variations in the number of neutrons mean that not all the atoms of an element possess the same mass. Atoms of an element that vary in their mass are known as isotopes of that element. The number of protons in the nucleus determines the atomic number (also called proton number), and the mass number is the sum of the numbers of protons and neutrons. The mass number is often written as a superscript in front of the symbol for the element. For example, there are seven isotopes of carbon: ^{10}C, ^{11}C, ^{12}C, ^{13}C, ^{14}C, ^{15}C, and ^{16}C (*see* CARBON CYCLE).

An atomic nucleus carries a positive electromagnetic charge owing to the protons it contains. The nucleus is surrounded by electrons. An electron is a particle carrying a negative charge that precisely balances the positive charge on a proton, and the electrons surrounding an atomic nucleus possess discrete amounts of energy that confine them to electron shells. An atom carries no electromagnetic charge if the number of electrons is equal to the number of protons in its nucleus. An atom that gains or loses one or more electrons carries a net charge and is said to be an ION.

Bonding between atoms occurs when two atoms share or exchange one or more electrons. There are three types of chemical bonding: covalent, hydrogen, and ionic. Metals form metallic bonds, which are also based on the attraction between protons and electrons.

A covalent bond is an attractive force that holds together two or more atoms that share an electron between them; if they share two electrons they form a double covalent bond. An oxygen atom (O), for example, forms covalent bonds with two hydrogen (H) atoms and forms a water molecule (H_2O), and a carbon (C) atom forms double covalent bonds with two oxygen atoms to form a molecule of carbon dioxide (CO_2). The gases oxygen and nitrogen occur in the air as molecules (O_2 and N_2) comprising two atoms joined by a covalent bond.

A hydrogen bond is an attractive force that links molecules in which hydrogen is bonded to nitrogen, oxygen, or fluorine. These are POLAR MOLECULES and the electrostatic attraction is between poles with opposite charge. In ammonia (NH_3), for example, there is a bond between the hydrogen (H^+) of one molecule and the strongly negative nitrogen (N^-) of an adjacent molecule. Oxygen atoms are also strongly negative and water molecules are linked by hydrogen bonds between the hydrogen of one molecule and the oxygen of its neighbor.

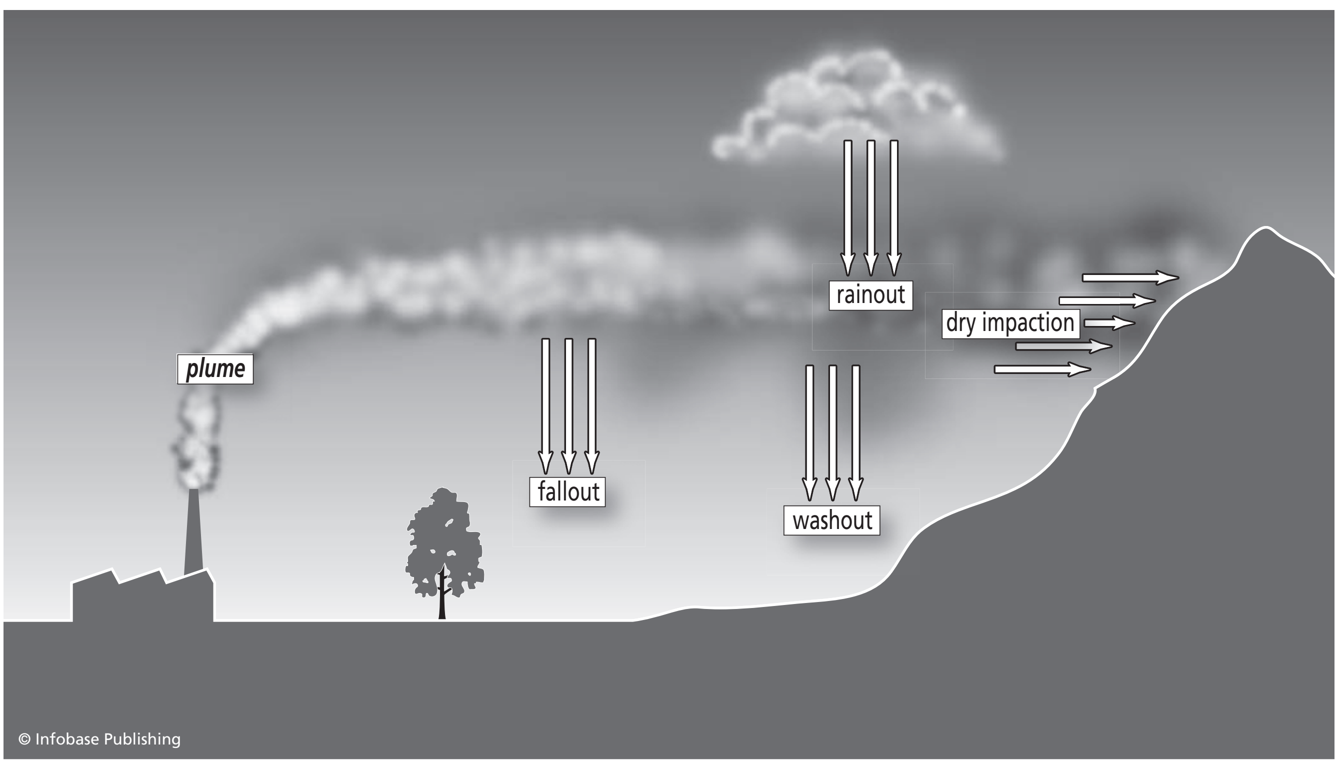
Hydrogen bonding differs from other types of chemical bonding in that it bonds molecules, not atoms. Hydrogen bonding in water causes the rearrangement of molecules on FREEZING that results in the density of ice being less than that of liquid water.

An ionic bond is an attractive force that holds together two or more atoms that exchange electrons between them. In the case of sodium chloride (NaCl), for example, sodium (Na) donates an outer electron to chlorine (Cl). Donating an electron produces a more stable electron configuration for both atoms, but leaves them charged, as Na^+ and Cl^-. The electrostatic attraction between positive and negative then bonds the two atoms together.

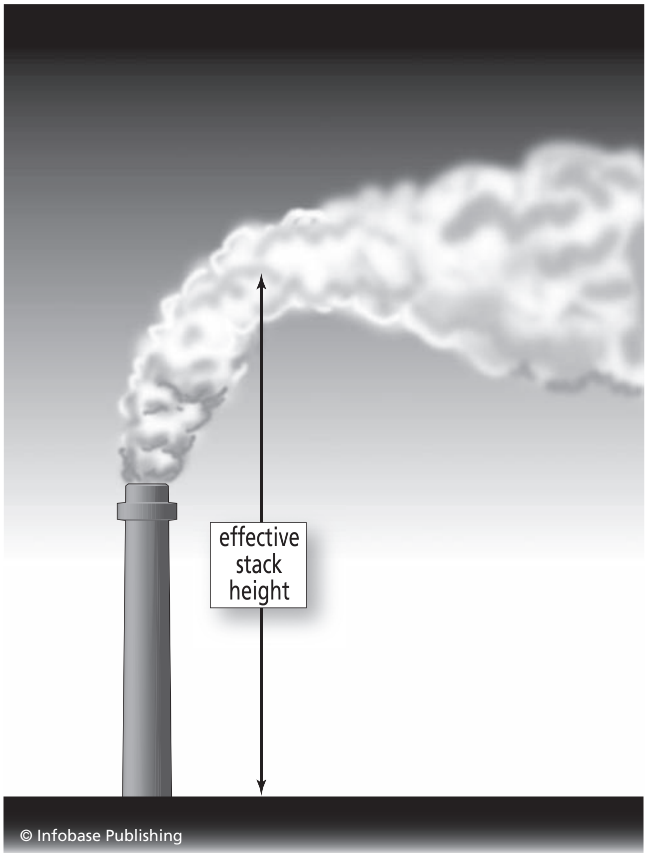
A metallic bond holds together the atoms in a solid metal. In a solid piece of metal the atoms have lost electrons and, therefore, carry a positive charge. The atoms are thus positively charged ions, or cations. The atoms are packed tightly together in a regular, three-dimensional lattice. Free electrons flow through the spaces between the atoms as an electron gas. These free electrons, from the outer electron shells of the atoms, are said to be delocalized, in contrast to the electrons of the inner shells, which remain attached to their nuclei and are said to be localized. The atoms are held in place by their attraction to the delocalized electrons, and the attraction extends throughout the lattice.

chill wind factor An index that was developed by the Canadian army to help in relating the performance of equipment to that of personnel in the arctic winter. The index is equal to the wind speed measured in miles per hour minus the temperature in degrees Fahrenheit. For example, a wind speed of 25 MPH at a temperature of -40°F would give an index of: 25 - -40 = 25 + 40 = 65. This is in no way connected to WIND CHILL.

chimney plume The cloud that is emitted from a chimney or factory smokestack and that travels downwind in one of the patterns known as coning, downwash, fanning, fumigating, lofting, looping, and trapping. The plume consists of gases, which are the chemical products



Gases and particles from the chimney are carried away by the wind, dispersing as they move farther from the source.



As it emerges from the stack, a chimney plume rises before bending over and heading downwind. The final height of the plume is the effective stack height.

of COMBUSTION. These are invisible. If the plume can be seen it is because of the presence of water droplets and possibly solid particles of ash and soot (*see* AIR POLLUTION). Water is also a product of the combustion of hydrocarbon fuels, through the oxidation of hydrogen.

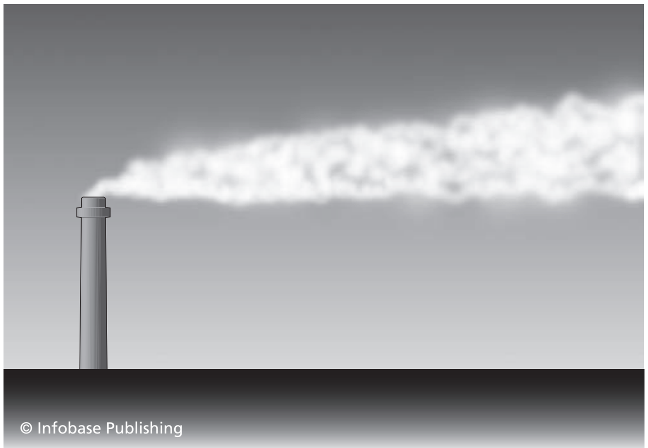
The stack height or chimney height is the actual height above the ground of the top of a factory smokestack (chimney). The stack height determines the height at which gaseous and particulate emissions enter the atmosphere. The more useful measurement, however, is that of the effective stack height, because this takes account of the vertical speed of the material leaving the stack.

The effective stack height is the height at which a chimney plume begins to move downwind after it has emerged from the top of a smokestack. Except in very strong winds, the plume does not move downwind immediately upon leaving the stack, because it is traveling vertically upward and is warmer than the air into which it discharges, and consequently it possesses BUOYANCY. The height to which a plume rises after leaving the top of the smokestack is known as the plume rise. Plume rise depends on the height, internal diameter and shape, and diameter at the mouth of the stack, on the temperature and exit velocity of the plume, and on the prevailing wind speed and LAPSE RATE. The effective stack height is equal to the sum of the height of the stack and the plume rise. The greater the effective stack height, the less pollution the plume will cause, especially close to the stack, because the plume will remain well clear of the ground for longer, giving more time for its contents to be diluted by mixing with the surrounding air.

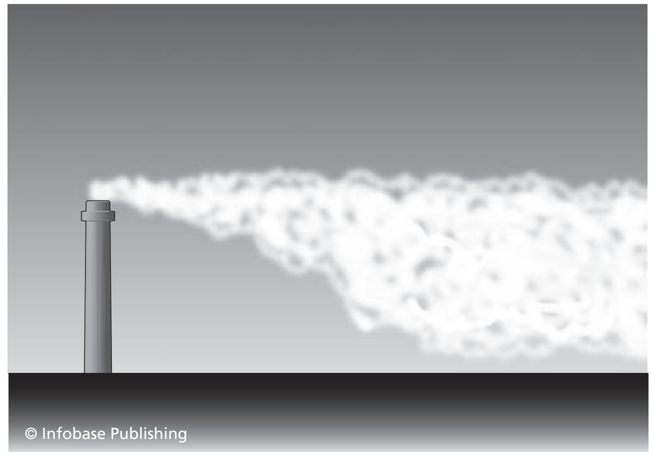
As the plume travels downwind, it mixes with the surrounding air and disperses. Dispersion is due to several processes. Heavier solid particles fall under gravity, as FALLOUT. In air that is close to SATURATION, smaller particles act as CLOUD CONDENSATION NUCLEI and trigger the formation of cloud. As the resulting CLOUD DROPLETS grow into RAINDROPS and fall as PRECIPITATION, the particles are removed from the air by a process known as rainout. Falling rain and snow also collide with other airborne particles, carrying them to the ground in a process known as washout. Finally, where the plume encounters solid surfaces, the molecules and particles in it will adhere by a process known as dry impaction.

In coning, the plume of gases and particles widens with increasing distance from the smokestack. An imaginary line drawn through the center of the plume is horizontal. Coning occurs when the wind is fairly strong and the plume is moving through stable air (*see* STABILITY OF AIR). In the layer of air extending from the surface to beyond the height of the plume the dry adiabatic LAPSE RATE is greater than the environmental lapse rate.

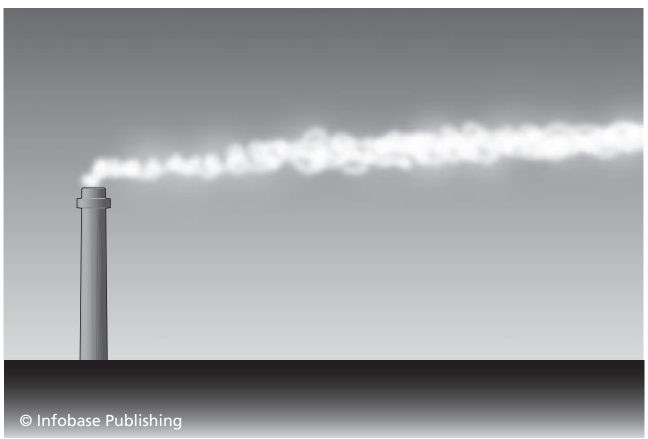
Downwash is the transport of air to the surface when it becomes caught in an EDDY on the LEE side of a hill or building. If the caught air is polluted, the pollutant will be brought to ground level. Pollutants will not disperse well from a chimney that is situated on the roof of a tall building if that building is surrounded by lower buildings and the top of the chimney is only a short distance from the roof. This is because the chimney plume will be carried downward by the eddy on the lee side of the building. Downwash will not happen if the chimney is tall enough to rise above the eddy. The plume from a chimney on the roof of a low



Coning occurs when the plume of gas and particles from a factory chimney travels horizontally, spiraling away downwind.



Fumigating occurs when the plume of gas and particles widens and sinks to ground level, causing serious pollution.



Fanning occurs when the plume of gas and particles moves downwind in a fairly straight line, without dispersing.

Lofting occurs when the plume of gas and particles rises gently as it travels downwind and disperses.

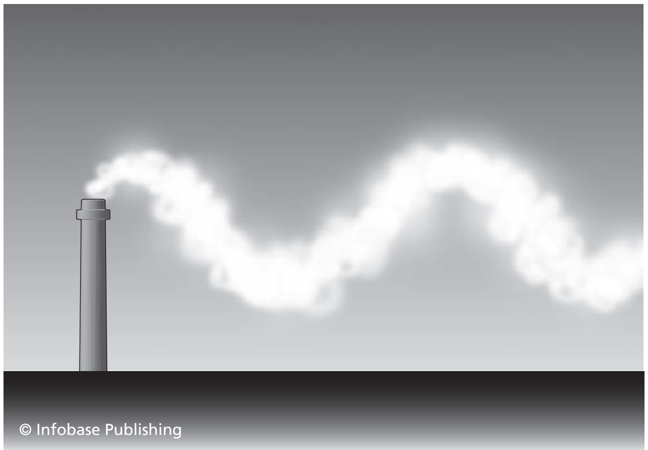
building that is located beside a taller building will also be caught in the eddy from the tall building and carried to the ground.

If the plume is fanning, the gases and particles travel smoothly and horizontally without dispersing. Fanning occurs when there is a strong INVERSION in the layer of air extending from the surface to beyond the top of the plume. In this situation the environmental lapse rate marks an increase of temperature with height. Fanning is sometimes seen early on winter mornings.

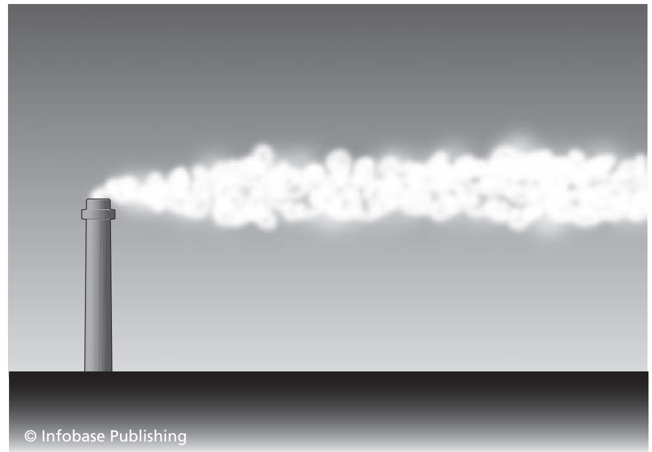
A plume that is fumigating widens and sinks with increasing distance from the smokestack. This brings the gases and particles to ground level, where they pollute the air. Fumigating occurs when the environmental lapse rate is greater than the dry adiabatic lapse rate in the layer of air extending from the surface to the height of the smokestack and there is also a strong inversion in the air above the stack.

A lofting plume widens with increasing distance from the smokestack and rises gently as it disperses. Lofting causes little or no pollution of air close to ground level. It occurs when there is an inversion extending only as high as the top of the smokestack and above the height of the stack the environmental lapse rate is greater than the dry adiabatic lapse rate.

In looping, the gases and particles descend toward the ground and then rise again, repeating this until the plume has dispersed. The plume causes pollution where its descent carries it close to ground level. Looping occurs when the wind is light and air is very unstable



Looping occurs when the plume of gas and particles moves downwind in looping spirals.



Trapping occurs when the plume of gas and particles widens and descends a little as it moves away, but there is little dispersion.

in the layer of extending from the surface to the top of the highest loop. In this layer the environmental lapse rate is greater than the dry adiabatic lapse rate.

Trapping is a pattern in which the plume widens a little and descends slightly with increasing distance from the smokestack, but there is little dispersion of the gases and particles. Trapping occurs when the dry adiabatic lapse rate is greater than the environmental lapse rate in the layer of air extending from the surface to the height of the smokestack and there is a weak inversion in the air above the stack.

circulation The movement of air or water along a path that eventually returns it to its starting point. Circulation can take place in either the horizontal or vertical plane. Air circulates vertically in a CONVECTION cell and the GENERAL CIRCULATION of the atmosphere involves a number of large-scale vertical cells (Hadley cells, Ferrel cells, and polar cells) that are combined in the three-cell model of the general circulation. The horizontal circulation of air may be cyclonic (*see* CYCLONE) or anticyclonic (*see* ANTICYCLONE) and the large-scale circulation may consist mainly of ZONAL FLOW or of MERIDIONAL FLOW.

The circulation pattern is the geometric shape of the horizontal anticyclonic or cyclonic circulation of the atmosphere as this is shown on synoptic charts (*see* WEATHER MAPS), where it is indicated by the isobars (*see* iso-).

Around the North and South Poles the westerly winds form a circulation pattern known as a circumpolar vortex. The winds of the circumpolar vortex circulate cyclonically around a persistent region of low pressure located in the troposphere (*see* ATMOSPHERIC STRUCTURE) at an altitude of 6,500–33,000 feet (2–10 km).

Horizontal flow is affected by periodic changes in the distribution of AIR PRESSURE, such as the NORTH ATLANTIC OSCILLATION, PACIFIC DECADAL OSCILLATION, and MADDEN-JULIAN OSCILLATION. Variations in the mean flow occur during ENSO events.

A center of high or low air pressure that is located in a particular position more or less permanently is known as a center of action. Centers of action are produced by the general circulation of the atmosphere, but changes in their shape, size, or intensity have widespread meteorological effects.

Circulation flux is a FLUX associated with the overall movement of the atmosphere—its circulation rather than EDDY motion.

A circulation index is a value ascribed to one of the major components of horizontal atmospheric circulation. There are two such indices, the meridional index and the ZONAL INDEX. Zonal flow varies over a cycle known as the index cycle.

clear air turbulence (CAT) Vertical air currents that occur in unstable air (*see* STABILITY OF AIR) that is not saturated and is therefore free from cloud.

There are several ways CAT can occur. Unstable air will rise by CONVECTION at FRONTS, where air is converging, and by being made to cross high ground. It can also do so where there is a sharp difference in surface temperature between two adjacent areas, such as the warm surface of a small island surrounded by the cool surface of water. Strong WIND SHEAR can also trigger instability, even in air that is stable when it is still. Wind shear associated with the JET STREAM is the commonest cause of the clear air turbulence that occasionally affects aircraft.

climate classification The arrangement of climates according to their most important characteristics in order to provide each type with a short, unambiguous name or title by which it can be known. This is necessary if climates are to be compared, because without names that everyone understands, all the relevant features of each climate would have to be repeated every time that climate was mentioned and discussions would become impossibly long-winded and confusing.

The word *climate* describes the average weather conditions that are experienced in a particular place over a long period. This is contrasted with the WEATHER that is experienced from day to day. The climate of a place is determined principally by its latitude, its distance from the ocean, and its elevation above sea level. This makes it possible to define the different types of climate.

The atmosphere, together with all the factors that affect it to produce the climates of the world, constitute the climate system. The system includes the oceans, lakes, rivers, and the HYDROLOGICAL CYCLE, the polar ICE SHEETS, the solid Earth, and living organisms. The energy driving the system is derived from the Sun, and solar radiation, and periodic changes in it, is also included as a component of the system.

The factors that determine the weather and climate of a particular region are known as climatic elements. There are seven elements of major importance: TEMPERATURE, sunshine, AIR PRESSURE, wind direction and speed, HUMIDITY, cloudiness, and PRECIPITATION. VISIBILITY is also a climatic element, but of less general importance.

These elements vary from place to place, their particular character being determined by climate controls. Latitude is the most important of these, because it defines the amount of solar radiation the place receives. The proportions of the surrounding area that have surfaces of land and water are also important, because of their different HEAT CAPACITIES. The geographic location of the place and the direction of the prevailing winds (*see* WIND SYSTEMS) determine the AIR MASSES that reach it. For instance, maritime air, with its moderating influence on temperatures, is carried a long way inland. Consequently, a place on the windward (*see* WIND) side of a continent will have a gentler climate than a place in the same latitude on the opposite side of the continent, where it will receive continental air. The movement of air masses may be blocked by mountain ranges, however. This is the case in North America, where the moderating influence of maritime air from the Pacific does not extend very far inland because of the Rocky Mountains. Mountains also receive OROGRAPHIC rain on the windward side and the lee side (*see* WIND) has a dry climate. This effect is seen in all the continents. Ocean currents also influence climates on land. Western BOUNDARY CURRENTS carry warm water, which warms the air crossing over it, and eastern boundary currents carry cold water. As well as affecting the air temperature, boundary currents also affect the humidity. Eastern boundary currents tend to produce very arid coastal climates and western boundary currents produce moist climates. The Atacama and Namib Deserts are located along coasts exposed to eastern boundary currents (the Peru Current and Benguela Current; *see* APPENDIX IV: OCEAN CURRENTS). The mild climate of northwestern Europe is the result of the warm North Atlantic Drift and Japan and the Aleutian Islands benefit from the Kuroshio Current.

The boundary between two or more regions that have markedly different types of climate is known as a climatic divide.

Before any group of things can be classified, their most important features must be identified. In the case of climates, the main features relate to temperature and precipitation. The earliest classifications were made in ancient Greece and took account of only temperature. The Greeks divided the Earth into three climatic regions that they called torrid, temperate, and frigid.

Attempts at more detailed classifications began in the 19th century. At first, they were made mainly by plant geographers, who were botanists and interested not so much in temperature and precipitation data as in the effects of temperature and precipitation on plant communities. Therefore, they related climates to the types of vegetation associated with them and some of the resulting names are still used. It is quite usual to speak of a "savanna" climate, for example, or a "tropical rain forest," "tundra," or "boreal forest" climate (the boreal forest is the predominantly coniferous forest that grows in the north of Canada and Eurasia). Other names, such as a "penguin" climate, have been dropped, although they were once in use.

When the first attempts at classification were being made, the only reliable information available referred to temperature, precipitation, and vegetation types. Much more information has become available since then. It is now possible for a classification to include data concerning the climatic requirements for crop growth, for example, or the effect of climates on humans living in them, and data can be obtained from satellite readings and images as well as from surface observations. Modern computing power also makes it possible to classify climates by means of extremely complex statistical analyses of the data.

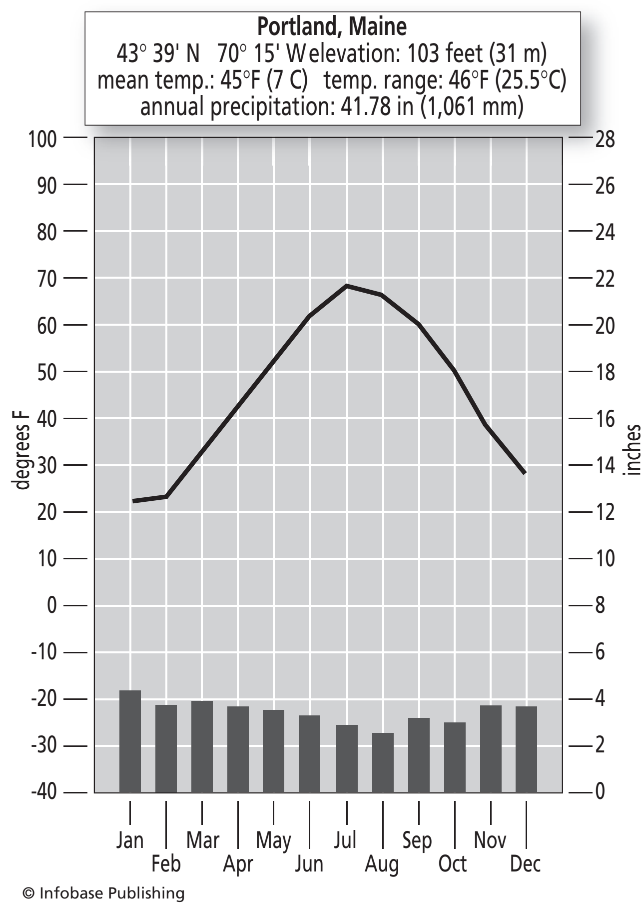
Most classifications are based on either a generic, or empirical, approach, or a genetic approach. Both are valid.

Generic classifications identify climates that are similar in their effects on plant growth. They rely on two primary criteria: aridity and warmth. Aridity takes account of both precipitation and temperature to determine the effective PRECIPITATION, which is what regulates plant growth. The most widely used of the generic classifications are those devised by Wladimir Köppen and C. W. Thornthwaite. The Russian climatologist M. I. Budyko (*see* APPENDIX I: BIOGRAPHICAL ENTRIES for information on all three) proposed a generic scheme in 1958 that is based on radiation and evaporation and introduces the concept of a radiational index of dryness.

Genetic classifications are based on those features of the general circulation of the atmosphere that cause particular climates to occur where they do. In other words, they relate climates to their physical causes rather than grouping similar types, as in generic systems. There are fewer genetic classifications than generic ones. H. Flohn proposed one such scheme in 1950 and in 1969 A. N. Strahler (*see* APPENDIX I: BIOGRAPHICAL ENTRIES for information on both) devised a classification that can be related to the Köppen classification.

No single scheme of climate classification is satisfactory for all purposes. Some provide no more than a convenient set of names. Many are intended mainly for agricultural application. Others relate to the distribution of natural vegetation and are of interest to geographers, botanists, and ecologists. Because classifications must serve so many different purposes, they tend to be more or less specialized and consequently a large number of schemes have been proposed, reflecting the particular interests of the climatologists who devised them. Further proliferation has resulted from the many attempts that have been made to produce a single, comprehensive scheme that suits the requirements of all users. Each scheme has its advantages and its limitations. Through them all, however, the Köppen and Thornthwaite classifications have emerged as the ones that are most widely used.

The climate of a particular place, such as a city or county, can be clearly illustrated by means of a climate diagram, which shows the mean temperature and precipitation month by month. There are several types of climate diagram, but the one most widely used has a scale for temperature on one side, with a curve showing the temperature through the year, and a scale for the amount of precipitation on the opposite side. Precipitation is usually shown as a histogram. The diagram below shows the name of the place to which the



In a climate diagram, the mean temperature for each month is shown by the line and the average precipitation by the bars. The diagram summarizes the climate for a particular place, in this case Portland, Maine.

data refer, often with its latitude and longitude, and additional information may also be displayed, such as height above sea level, the total annual precipitation, and temperature range.

There is often considerable climatic variation within an area the size of a continent and climatologists also classify climates according to their geographic scale. A macroclimate is typical of a very large area, such as a continent or the entire Earth. This is the largest of the scales climatologists use. In the widely used climatological classification introduced by the Japanese climatologist M. M. Yoshino, a macroclimate is designated Mc. The study of macroclimates is called macroclimatology.

The climate of a large area that can be defined by a particular physical characteristic is called a mesoclimate. For example, the climate typical of a grass-covered plain, such as the Great Plains of North America and the steppes of central Asia, or of a large mountain range constitutes a mesoclimate. A mesoclimate extends vertically to about 20,000 feet (6,000 m). In the Yoshino classification, mesoclimates are designated Ms_1 to Ms_3.

Ms_1 plain
Ms_2 mountains
Ms_3 basin area

The study of mesoclimates is known as mesoclimatology.

The climate of a very small area when this can be clearly distinguished from the climate of the surrounding area constitutes a microclimate. A forest clearing has a climate that differs from that of the surrounding forest, so this constitutes a microclimate. A city street lined on both sides by tall buildings has a microclimate, as does the side of a hill. On a still smaller scale, on land covered by low-growing vegetation, such as grass or a field crop, there is a microclimate between the ground and the top of the vegetation. A variation in a microclimate that is directly due to a difference in elevation of the area experiencing it is called a contour microclimate. In the Yoshino classification microclimates are designated M_1 to M_6.

M_1 corn field
M_2 forest clearing
M_3 city canyon
M_4 hill slope
M_5 ice field
M_6 grass cover

Microclimate is the smallest of the scales used by climatologists. The study of microclimates is known as microclimatology.

The microclimate found within an area that has a distinct type of surface forms a local climate. Taken together, the microclimates of an area such as a forest, farm, or city constitute a local climate. A local climate affects an area from 2.5 acres (1 hectare) to 39 square miles (100 km^2) and to a height of about 330 feet (100 m) above the surface. In the Yoshino classification local climates are designated L_1 to L_7.

L_1 croplands
L_2 broad-leaved forest
L_3 city
L_4 coniferous forest
L_5 and L_6 mountain environments
L_7 intermontane grassland.

Climate-Leaf Analysis Multivariate Program (CLIMAP) A program that uses plant leaves to help estimate past temperatures. Leaves of dicotyledonous plants (those with seeds that produce two seed leaves, or cotyledons) that are known to have been present at a site at a known time in the past are subjected to a statistical analysis of a suite of 29 characteristics. The technique is based on the strong correlation that has been observed between the warmth of the climate and the likelihood that dicotyledonous plants will have leaves with smooth edges.

Climate: Long-Range Investigation Mapping and Prediction (CLIMAP) A ten-year international scientific project, the aim of which was the reconstruction of the climates of the QUATERNARY sub-era. The project ran from 1971 until 1980 and was funded by the National Science Foundation and administered from Columbia University, New York. It involved the participation of scientists who specialize in Earth and atmospheric sciences and oceanography. CLIMAP has been succeeded by the COOPERATIVE HOLOCENE MAPPING PROJECT.

climate model A mathematical simulation of the processes that affect the atmosphere and produce local WEATHER and the climates over large regions, or the entire world, and over extended periods. It is used as an aid to understanding those processes and predicting how changes to them may affect weather and climate. The model consists of a computer program in the form of a series of equations that allow the physical laws controlling the weather to be applied (*see* GAS LAWS). This is possible only to a limited extent, because not all climatic processes are fully understood, data is incomplete, and if the model is to describe conditions over a large region or long period of time the amount of computation involved may exceed the capacity of the available computers. Consequently, climate models are necessarily simplified.

Construction of most models begins with the imposition of a grid over the region to be studied. The grid may be two-dimensional or three-dimensional, like a cage made from several two-dimensional grids placed one above the other and linked vertically. Two-dimensional models may represent two horizontal dimensions, like the lines of latitude and longitude on a map, or, more commonly, the vertical and one horizontal dimension.

Initial data on such factors as AIR PRESSURE, TEMPERATURE, HUMIDITY, CLOUD AMOUNT and CLOUD TYPE, and wind speed and direction are supplied to each intersection between grid lines, which is where all the calculations of physical effects are made. Conditions at every intersection affect those at every other because of FEEDBACK, which may be negative or positive, so a formidable amount of computation is needed to trace the development of a storm, for example, or a frontal system (*see* FRONT). When conditions change at one intersection, the results of that change supply the input data for adjacent intersections, where conditions are then recalculated. In this way the entire system evolves, usually in a "time-step" fashion.

The sensitivity of the model depends on the scale of the grid—the distance between grid lines—and the size of the time steps—the shorter these are the more accurate the model is likely to be. Obviously, however, reducing the distance between grid lines or time intervals greatly increases the number of calculations and, therefore, the computing power needed to run the model.

Models must be tested before they can be used to estimate the consequences of change. Testing usually begins by supplying the model with data from the recent past then running it to see how well it simulates the weather conditions that were actually recorded. If this is successful, the model is used to simulate conditions from the more distant past, partly as an aid to understanding how those conditions developed. Only if it passes these tests is the model used to estimate what may happen in the future.

Some models are one-dimensional and not based on a grid. Radiative convective models, for example, calculate the vigor of CONVECTION in a vertical column through the atmosphere. They do this by calculating the effects of incoming and outgoing radiation and computing the amount of convective motion needed to produce a known LAPSE RATE.

The most powerful supercomputers are used to construct and run the more complex models and the reliability of models is directly proportional to the amount of computational power that is available to run them. Regardless of the amount of computational power, however, all models make assumptions about factors that are not well understood, such as the role of ocean currents in the transport of heat, and that occur on a scale much smaller than that of the grid, such as CLOUD FORMATION.

Clouds produce cloud shadow—the shading of the ground by a cloud that is overhead. This is the primary cause of reduced sunshine. Climate models must include broad assumptions about the effect of cloud shadow, because clouds form on a scale too small to be captured by the model grid. Despite its importance, cloud shadow is one of the least understood phenomena in theories of climate change.

An analog model aims to match present atmospheric conditions to times in the past when similar conditions prevailed and then to use the way the past conditions developed to predict the development of the present conditions. Analog models are used mainly in long-range weather forecasting and in climatological studies of ways the global climate may be changing. Concerns about GLOBAL WARMING, for example, have generated interest in warm periods that occurred in the early part of the PLIOCENE epoch about 4.3–3.3 million years ago, during the Eemian INTERGLACIAL of northern Europe about 130,000–72,000 years ago, and in the CLIMATIC OPTIMUM that occurred about 5,000 years ago. The HOLOCENE climatic optimum is the subject of the COOPERATIVE HOLOCENE MAPPING PROJECT.

Many climate models base their calculations on a polytropic atmosphere. This is a hypothetical atmosphere which is in hydrostatic equilibrium (*see*

HYDROSTATIC EQUATION) and its temperature decreases with height at a constant lapse rate.

There are several types of models. A climatic prediction is an estimate of the possible climatic consequences of social or industrial changes that are already occurring and that are likely to continue. For example, as cities grow in size their heat production can be calculated fairly accurately (*see* HEAT ISLAND) and from this it is possible to estimate the effect on summer and winter temperatures and precipitation. Models that calculate the effect of releasing greenhouse gases (*see* GREENHOUSE EFFECT) into the atmosphere estimate the climatic consequences at various times in the future. These are also climatic predictions.

A chemical transport model (CTM) is a three-dimensional model that uses observed or analyzed winds, moisture, temperature, and other meteorological conditions to calculate the transport of chemical substances through the atmosphere and reactions among them as a function of time. A CTM includes the processes by which chemical species are converted to AEROSOLS and by which they are incorporated into rain and washed to the ground. The models can therefore be used to compute the way the distribution of aerosols varies from place to place and time to time.

A crop yield model relates local weather conditions to crop yields. Farmers can use such models to help in planning farming operations. The models take account of temperature, water availability, carbon dioxide, and sunshine. They also make some allowance for crop pests and diseases, the seriousness of which is partly related to climate. Relationships between weather and yield for particular crops are often based on historical records.

An energy balance model (EBM) describes the change in sea-level temperature with latitude and the balance of energy input and output in each latitudinal belt. Such a model is one-dimensional (it deals only with temperature changes with latitude in a horizontal plane) but its simplicity means it can be installed and run on small computers. The model is used as an instructional tool and also to check the accuracy of more complex models. The relationship it describes is summarized by:

$$\rho C\Delta T(\theta) \div \Delta T = R{\downarrow}(\theta) - R{\uparrow}(\theta) + \text{transport into belt } \theta$$

where ρC is the HEAT CAPACITY of the area being studied, ΔT is the change in temperature, θ is the latitudinal belt, $R{\downarrow}$ is the radiant energy entering the system, and $R{\uparrow}$ is the infrared radiation (*see* SOLAR SPECTRUM) leaving the system.

A general productivity model interprets climatic conditions in order to predict agricultural production throughout the major farming regions of the world. This makes it possible to estimate future commodity prices and, from that, to plan production in particular areas.

A historical analog model is based on comparisons with weather conditions that obtained at some time in the past. It is an analog MODEL because it uses comparisons, rather than calculations of physical values for pressure, temperature, and precipitation. When estimating the possible consequences of increasing the atmospheric concentration of CARBON DIOXIDE, for example, modelers might study the global distribution of temperature and precipitation during periods in the past when the CO_2 concentration is estimated to have been higher than it is today. Alternatively, future changes can be estimated from the difference in the conditions that prevailed during the five coldest and five warmest years over a 50-year period.

A statistically dynamical model is a two-dimensional climate model that deals only with surface processes. It describes the latitudinal (toward and away from the equator) transport of energy and the vertical distribution of energy by radiation and convection.

A storm model simulates the way air and water vapor move into, out of, and vertically within a storm.

In a swamp model, the oceans are treated as though they were permanently wet land—in fact, a swamp. The wet surface in a swamp model has no heat capacity or active mechanisms for transferring heat. Swamp models were constructed because of the difficulties and uncertainties involved in describing mathematically the thermal behavior and movement of the real ocean. Modern models are better able to do this and so swamp models are no longer used.

climate types All systems of CLIMATE CLASSIFICATION break down the climates of the world into a limited number of general types.

In the THORNTHWAITE CLIMATE CLASSIFICATION, an arid climate is one in which the moisture index is between –100 and –67 and the potential EVAPOTRANSPIRATION is 5.6–11.2 inches (14.2–28.5 cm). It is designated E.

A boreal climate is associated with the belt of coniferous forest that lies across North America and Eurasia (in Russia it is known as the "taiga"). The name *boreal* refers to Boreas, the Greek god of the north wind. The region is bounded by the edge of the tundra in the north and extends southward to about 55°N in eastern North America and about 60°N in the west. In Eurasia it extends to about 50°N in the east and 65°N in the west.

The boreal climate extends farther south in the east of the continents because it is within the midlatitude belt of westerly winds that carry AIR MASSES from west to east. Air masses entering North America and Eurasia from the Pacific and Atlantic respectively are maritime and therefore moist and relatively mild. As they cross the continents, they become increasingly continental, making them drier and more extreme in temperature.

Summers are short, with average temperatures that reach about 60°F (15°C), but maximum temperatures that can be much higher. A temperature of 99°F (37°C) has been recorded at Fairbanks, Alaska, and Yakutsk, Siberia, has known 102°F (39°C). Winter is the dominant season, however. It lasts from six to nine months, during which the temperature remains below freezing. In many places away from coasts there are up to four months when the temperature remains below 0°F (-18°C). The Northern Hemisphere COLD POLE lies within this region. Heat is radiated away from the snow-covered ground so rapidly that in winter there is often a more or less permanent temperature INVERSION and the LAPSE RATE is negative (temperature increases with height) from ground level to a height of 3,300–5,000 feet (1,000–1,500 m). The range of summer and winter average temperatures is greater than in any other climate, typically of about 60°F (33°C).

Precipitation is generally light. Fairbanks has an average of about 12 inches (305 mm) a year and Yakutsk about 14 inches (356 mm). Coastal areas receive rather more. Archangel, in northern Russia, has about 21 inches (533 mm), for example, and Trondheim, Norway, has about 40 inches (1,016 mm).

A continental climate is produced by continental air (*see* air mass). It occurs in areas deep in the interior of continents, far from the ocean. Air loses its moisture as it crosses the continent, making continental climates dry. Because of the large difference in HEAT CAPACITY between water and land, the continental interior heats rapidly in summer and cools rapidly in winter, producing a much wider annual temperature range than that of a maritime climate in the same latitude. Omaha, Nebraska, has a typical continental climate. Its annual temperature range is 73°F (41°C) and its average annual precipitation is 29 inches (737 mm). Eureka City, in Humboldt County, California, is in the same latitude as Omaha, but lies on the western coast, where it enjoys a maritime climate. There the annual temperature range is 22°F (12°C), and the average annual precipitation is 38 inches (965 mm).

The climates of Omaha and Eureka are extreme examples of their types. In other places the maritime or continental influence is less extreme, and its extent can be calculated as the CONTINENTALITY or OCEANICITY of the climate.

In the climate classification devised by A. N. Strahler (*see* STRAHLER CLIMATE CLASSIFICATION), a continental subarctic climate is a climate in his Group 3, comprising climates controlled by polar and arctic air masses. The continental subarctic climate occurs in source regions (*see* AIR MASS) for continental polar air in latitudes 50°–70°N. In winter, the air is stable (*see* STABILITY OF AIR) and extremely cold. Summers are cool and short. There is a very large range of temperature through the year. The climate is moist, but this is because the rate of evaporation is low, not because there is heavy precipitation. Precipitation is light and falls during storms associated with frontal systems (*see* FRONT) involving maritime polar air. This is a cold, snowy forest, or humid microthermal, climate. In the KÖPPEN CLIMATE CLASSIFICATION, if a climate of this type is moist throughout the year, it is designated Dfc if summers are cool and Dfd if summers are cool but winters extremely cold. If the winter is dry, it is designated Dwc if the summers are cool and Dwd if winters are very cold.

A cotton-belt climate has warm, wet summers and dry winters. It occurs on the eastern sides of continents and is characteristic of the cotton-growing regions of the southern United States and China.

In the climate classification devised by Mikhail I. Budyko (*see* BUDYKO CLASSIFICATION and APPENDIX I: BIOGRAPHICAL ENTRIES), a desert climate is one in which the radiational index of dryness has a value of more than 3.0.

In a dry climate the average annual precipitation is less than the potential evapotranspiration, and plant growth is restricted by the lack of moisture. In the

Köppen climate classification, dry climates are designated category B and include the semi-arid steppe (categories BSh and BSk) and desert climates (categories BWh and BWk).

In the Thornthwaite climate classification, dry climates are those with a moisture index lower than zero. These include the dry subhumid (category C_1, with a moisture index between -20 and 0), semi-arid (category D, with a moisture index between -40 and -20), and arid (category E, moisture index between -60 and -40) climates.

An equatorial climate occurs in the region approximately bounded by latitudes 10°N and 10°S. It is warm and humid throughout the year, with little seasonal variation. This is the climate of tropical rain forests, known as the wet equatorial climate in the Strahler climate classification.

A forest climate has a radiational index of dryness of 0.33–1.0 in the Budyko climate classification.

A grasslands climate, also called a prairie climate or subhumid climate, is a climate in humidity province C in the Thornthwaite climate classification, with a precipitation efficiency index of 32–63.

A highland climate is a climate in Group 3 of the Strahler climate classification. This comprises climates controlled by polar and arctic AIR MASSES. Highland climates occur at high altitudes in mountain ranges throughout the world. They are cool and moist, but local in extent.

A humid climate, in the Thornthwaite climate classification, is one in which the moisture index is between 20 and 100 and the potential evapotranspiration is 22.4–44.9 inches (57–115 cm). There are 4 subdivisions (B_1 to B_4). In terms of thermal efficiency, this is a mesothermal climate (B'_1 to B'_4).

In the Strahler classification a humid continental climate is one in Group 2, comprising climates controlled by both tropical and polar air masses. Humid continental climates occur in latitudes 35°–60°N in the central and eastern regions of continents, where polar and tropical air masses meet. The weather is very variable, and there are strong contrasts between summer and winter. Precipitation is abundant and increases in summer, when maritime tropical air masses enter. Winters are dominated by continental polar air masses that invade frequently from the north. This climate type includes the cold, snowy forest, or humid microthermal, climate. It is designated Dfa in the Köppen classification if it is wet throughout the year and the summers are hot and Dfb if they are warm, Dwa if winters are dry and summers hot and Dwb if winters are dry and summers warm.

A humid subtropical climate is a climate in Group 2 of the Strahler classification, comprising climates controlled by both tropical and polar air masses. Humid subtropical climates occur in latitudes 20°–35° in both hemispheres, along the eastern edges of continents exposed to moist maritime tropical air masses that move from the western side of oceanic high-pressure cells. Summers are hot, with heavy rain. Winters are cool and often affected by polar air masses, and there are frequent storms produced by frontal systems. This climate includes the temperate rainy, or humid mesothermal climate, and is designated Cfa in the Köppen classification.

An icecap climate in the Köppen classification is the type of climate found over the GREENLAND ICE SHEET and the Antarctic ICE SHEET, which are source regions for arctic and Antarctic air masses. This is the coldest climate in the world. Temperatures never rise above freezing, the high elevation of the ice sheets intensifying the cold, and precipitation is very low. At the South Pole, where the ice surface is about 9,200 feet (2,800 m) above sea level, the annual precipitation is about 1 inch (25 mm) and the mean temperature is about -58°F (-50°C). Over the Greenland ice sheet, at an elevation of 9,900 feet (3,020 m) the mean temperature is about -22°F (-30°C) and annual precipitation is about 2.6 inches (67 mm). The icecap climate is also classed as a polar or perpetual frost climate and is designated EF in the Köppen classification.

In the Strahler climate classification an icecap climate is in Group 3, comprising climates controlled by polar and arctic air masses.

An insular climate occurs over an oceanic island or a coastal region, where the influence of the ocean is greater than that of the nearest large land mass. Although insular climates vary considerably, they are generally moister than continental climates and experience a smaller temperature range.

A marine subarctic climate is one in Group 3 of the Strahler classification, comprising climates controlled by polar and arctic air masses. Marine subarctic climates occur in latitudes 50°–60°N and 45°–60°S, along coasts and on islands exposed to frontal zones (*see* FRONT) involving maritime polar and continental polar air masses. Precipitation is fairly heavy, and there is a fairly small temperature range through the year. This is a polar or tundra climate designated ET in the Köppen classification.

A marine west-coast climate is in Group 2 of the Strahler classification, comprising climates controlled by both tropical and polar air masses. Marine west-coast climates occur in latitudes 40°–60° in both hemispheres, along western coasts that are exposed to frequent storms produced by frontal systems associated with cool, moist, maritime polar air masses. Precipitation is distributed fairly evenly through the year, but with a maximum in winter. The climate is cloudy, and the temperature range through the year is small. This type of climate includes temperate rainy, or humid mesothermal climates, designated Cfb in the Köppen classification if the summer is warm and Cfc if it is short and cool.

A maritime climate, also known as an oceanic climate, is produced by maritime air and occurs in areas close to the sea. Because of the influence of the sea, the seasonal temperature range is smaller than that of an area with a continental climate and precipitation is higher. In Fiji, for example, the annual temperature range is 4.9°F (2.7°C) and the average annual precipitation is 119 inches (3,026 mm). Although their latitude makes the Falkland Islands (Malvinas) colder and drier than Fiji, the corresponding figures are 3.6°F (2.0°C) and 25.6 inches (651 mm).

Bulawayo, Zimbabwe, is in about the same latitude as Fiji and Saskatoon, Saskatchewan, is in about the same latitude as the Falklands. Both these cities are in the interior of continents. In Bulawayo, the annual temperature range is 40°F (22°C) and the average annual precipitation is 23.5 inches (597 mm). In Saskatoon the annual temperature range is 88°F (49°C), and the average annual precipitation is 15 inches (381mm).

In middle latitudes, the prevailing winds (*see* wind systems) are westerlies. These carry air masses from west to east. Consequently, maritime climates occur on the western coasts of continents. Despite their proximity to the ocean, the eastern coasts of middle-latitude continents are affected by air that has crossed the continent to reach them and this produces climates closer to the continental type. Islands, such as Fiji and the Falklands, have climates of the most extreme maritime type and a place like Saskatoon, that is located near the center of a large continent, has an extreme continental climate. In other places the maritime or continental influence is less extreme and its extent can be calculated as the continentality or oceanicity of the climate.

A Mediterranean climate is in Group 2 of the Strahler classification, comprising climates controlled by both tropical and polar air masses. Mediterranean climates occur in latitudes 30°–45° in both hemispheres and are characterized by seasonal alternations between conditions typical of west-coast desert climates and those of marine west-coast climates. Winters are wet and summers dry. In winter, maritime polar air masses predominate, producing frontal systems with storms and abundant rain. In summer, maritime tropical air masses predominate, producing dry weather. DROUGHTS are common. There is a moderate range of temperature through the year. This type of climate includes temperate rainy, or humid mesothermal climates, and is designated Csa in the Köppen classification if the summer is dry and hot, and Csb if the summer is dry and warm.

Mesothermal is an adjective that describes a midlatitude climate in which the mean temperature in the coldest month is higher than -3°C (26.6°F). *Microthermal* is an adjective that describes a midlatitude climate in which the mean temperature in the coldest month is lower than -3°C (26.6°F). Both terms were introduced in connection with the Köppen climate classification.

Middle-latitude desert and steppe climates are in Group 2 of the Strahler classification, comprising climates controlled by both tropical and polar air masses. Climates of these types occur in latitudes 35°–50° in both hemispheres in continental interiors where mountains prevent maritime tropical or polar air masses from penetrating. The climates are dominated by continental tropical air masses in summer and continental polar air masses in winter. These produce a very large temperature range through the year, with hot summers and cold winters. Desert climates are designated BWk in the Köppen classification if they are cool and BWk′ if they are cold. Steppe climates are designated BSk if they are cool and BSk′ if they are cold.

A moist climate is one in which the amount of annual precipitation exceeds the annual potential evapotranspiration. In the Thornthwaite classification this is any climate with a moisture index greater than zero. In this classification moist climates belong to categories A, B, and C_2.

A moist subhumid climate in the Thornthwaite classification is one in which the moisture index is between 0 and 20 and the potential evapotranspiration is 11.2–22.4 inches (28.5–57 cm). The climate is designated C_2. In terms of thermal efficiency, this is a microthermal climate (C'_1 to C'_2).

A mountain climate differs from the climate typical of the latitude in which it occurs by reason of the high elevation of the land. The climatic effect of increasing elevation is broadly similar to that of increasing latitude, but there is wide variation in the types of mountain climates. Generally, mean temperatures are lower and conditions are windier. Precipitation is greater at lower levels on a mountainside, but above the permanent SNOW LINE precipitation decreases, because the air has lost most of its moisture. Air DENSITY decreases with elevation. This reduces the capacity of the air to retain heat. Consequently, the contrast in temperature between daytime and night and between places exposed to full sunshine and those in shade is greater on mountains than it is at sea level, regardless of latitude. Mountains are often shrouded in cloud. At the surface this is identical to FOG, but it is caused by OROGRAPHIC lifting and makes most mountain climates much foggier than low-level climates. Mountainsides also experience KATABATIC WINDS, which can warm the air below the summit and remove snow rapidly. Beyond such generalizations, however, the climate of a particular mountainside is affected by such factors as the direction it faces, the amount of shelter and shading it receives from surrounding mountains, and funneling effects (*see* WIND SPEED) on the prevailing wind.

In the Thornthwaite classification a perhumid climate is one in which the monthly moisture index is greater than 100 and the monthly potential evapotranspiration is greater than 44.9 inches (114 cm). It is designated A. In terms of thermal efficiency, this climate is megathermal (*A′*).

A periglacial climate is the type that prevails near the edge of an ICE SHEET. Its most distinctive feature is the frequency of cold, dry winds that blow outward from the semipermanent ANTICYCLONE over the ice sheet. This means the periglacial climate is cold and dry. There is a PERMAFROST layer beneath the surface, but the active layer thaws during the summer. During the brief thaw the soil of the active layer loosens and large rocks tend to start sliding downhill, but before they can travel far the ground freezes once more. Repeated cycles of freezing and thawing gradually arrange the rocks in patterns that can be recognized long after the climate has ceased to be periglacial. These patterns provide one of the clues that are used by paleoclimatologist (*see* CLIMATOLOGY).

A polar climate occurs in high latitudes where the mean monthly temperature remains below freezing throughout the year. Lichens and mosses may grow sparsely where the land surface is free from ice and snow, but otherwise there is no vegetation. There is no land at the North Pole. There, some thawing of the sea ice occurs in summer, producing slushy areas and stretches of open water.

During summer the hours of daylight are long. Everywhere inside the Arctic Circle and Antarctic Circle (*see* AXIAL TILT) there is at least one day when the Sun does not sink below the horizon. At the poles themselves this period of "midnight Sun" lasts about six months. Despite this, the Sun remains fairly low in the sky and the sunlight is not very intense. During winter the days are very short. At Murmansk, in northern Russia, the Sun remains above the horizon for 70 days during the summer, but is below the horizon from November 26 until January 20. Nevertheless, SCATTERING and REFRACTION allow some sunlight to reach the surface when the Sun is less than 18° below the horizon. This dim light that results is called astronomical twilight. There is also moonlight, starlight, and auroras (*see* OPTICAL PHENOMENA) to provide light, so the darkness is seldom total.

At Eismitte, the station at an elevation of 9,941 feet (3,032 m) near the center of the GREENLAND ICE SHEET that was established by Alfred Wegener (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), the mean annual temperature is -22°F (-30°C). The coldest month is February, when the mean temperature is -53°F (-47°C) and the warmest month is June, when the mean temperature is 4°F (-15.5°C). At Little America, close to sea level in Antarctica, the mean annual temperature is -14°F (-25.5°C). July is the coldest month, with a mean temperature of -39°F (-39.4°C), and the warmest month is February, when the mean temperature is 7°F (-13.9°C).

Together, the amount of solar radiation that is reflected by the snow and ice over the Arctic Ocean and the amount of heat emitted by the sea as infrared radiation (*see* SOLAR SPECTRUM) exceed the amount reaching the surface from the Sun by 60 percent. Temperatures over the Arctic Ocean are much higher than this would suggest, however, because ocean currents bring in warm water. The water then releases heat by radiation and CONVECTION. Water from the Gulf Stream (*see* APPENDIX IV: OCEAN CURRENTS) keeps the Norwegian and Barents Seas open throughout the winter. Even in the coldest areas of the Arctic Ocean, the sea-surface temperature does not fall below 29°F (1.7°C).

In winter, the sea ice covers an area of about 4.5 million square miles (11.7 km^2). The ice drifts from east to west and this movement causes it to crack, leaving open spaces, called "leads," even at the North Pole. In summer, the ice melts from the coasts of the surrounding continents until it occupies about 3 million square miles (4.8 km^2). For about two months in summer the Ocean is sometimes mainly open, with patches of drifting ice.

There are three principal types of polar climate, known as polar wet, polar wet-and-dry, and polar dry.

A polar dry climate is found over the continent of Antarctica away from the coast. It is produced by continental polar (cP) air and is type EF in the Köppen classification and EF′ in the Thornthwaite classification. Over most of Antarctica more energy is lost from the surface by reflection (*see* ALBEDO) and infrared radiation than is received from the Sun. This is possible because warmth that is carried into the region by ocean currents and the circulation of the atmosphere is lost to space. Consequently, Antarctica is the part of the world where the loss of surplus heat helps maintain a constant global mean temperature.

There are several reasons for the extremely low temperatures over Antarctica. It is a continent and therefore does not benefit from the moderating influence of maritime air (*see* CONTINENTALITY). Also, its elevation is generally high. At the South Pole the surface of the ice sheet is 10,000 feet (3,000 m) above sea level, and VOSTOK STATION is at an elevation of 11,401 feet (3,475 m). Finally, the South Pole receives 7 percent less solar radiation during its winter than the North Pole receives during its winter. This is because the elliptical orbit of the Earth places the South Pole 3 million miles (4.8 million km) farther from the Sun at the June SOLSTICE than the North Pole is at the December solstice. The coldest temperatures occur a few days after the Sun has risen above the horizon.

At the Amundsen–Scott Station, at the South Pole, the mean annual temperature is -56.8°F (-49.4°C). August is the coldest month, when the mean temperature falls to -75.9°F (-60.0°C). The warmest month is January, when the mean temperature rises to -18.7°F (-28.2°C). Precipitation is very low, probably not exceeding an annual mean of 2 inches (50 mm), and the relative HUMIDITY can fall to 1 percent. Winds are strong, especially in winter. They are KATABATIC WINDS produced by air moving gravitationally away from the higher elevations often with enough force to overcome the PRESSURE GRADIENT. The winds are strongest when the pressure gradient coincides with the topographic gradient. Then they routinely exceed hurricane force (75 MPH, 121 km/h).

A polar wet-and-dry climate is typical of the coastlines surrounding the Arctic Ocean, along the northern coasts of Canada, Alaska, and Eurasia, and around Greenland, Iceland, and the smaller northern islands. This climate also occurs over the islands in the Southern Ocean. About 5 percent of the total land area of the Earth experiences this type of climate. It is produced by mP (maritime polar) and cP (continental polar) air and supports tundra vegetation, comprising lichens, mosses, sedges, grasses, herbs, shrubs, and low-growing trees.

Winters are cold, summers cool, and most of the precipitation falls in summer, so the summer is cloudy and wet and the winter is dry, with generally clear skies. The relative humidity averages 40–80 percent in summer and 40–60 percent in winter. It is an ET climate in the Köppen classification and E′ in the Thornthwaite classification. The mean annual temperature is below freezing, but temperatures rise above freezing in summer. During the summer, which lasts for an average of two to three months but in some places for as long as five months, mean temperatures seldom exceed 41°F (5°C), although on some days the temperature may rise to about 80°F (27°C). Winds are usually light and variable in direction and storms are rare. Subsiding air on the high-latitude side of the polar cell (*see* GENERAL CIRCULATION) produces high surface pressure and fairly still air, especially in winter.

A polar wet climate is typical of the Southern Ocean surrounding Antarctica. It is produced by maritime polar (mP) air and is type Em in the Köppen classification and type AE′ in the Thornthwaite classification. The relative humidity is always high, with a yearly average of 50 percent, and the sky is usually cloudy. Cloud cover averages 80 percent during the winter and is rather less in summer. The amount of precipitation varies from place to place depending on the latitude, but there is at least a 25 percent chance of precipitation on any day and there is little seasonal variation in any one place. Precipitation amounts range from 14.6 inches (370 mm) to 115 inches (2,920 mm). Summer temperatures can rise to 50°F (10°C). In winter the temperature averages 19–32°F (-7–0°C). Storms are common, especially in winter. The gales associated with these storms led sailors to call the latitudes in which they occur the roaring forties, furious fifties, and shrieking sixties.

A rain forest climate is in humidity province A in the Thornthwaite classification, with a precipitation efficiency index greater than 127.

A rainy climate is one in which the amount of rainfall is adequate to support the growth of plants that are not adapted to dry conditions. In the Köppen classification it is classed as A (tropical forest) or C (warm temperate rainy). In the Thornthwaite classification it is a climate in the humidity provinces A and B.

The savanna climate sustains tropical grasslands, where the vegetation resembles open parkland, with tall grasses and scattered trees and shrubs. The trees and shrubs are small, umbrella-shaped, and drought-resistant, and they are most abundant in places where the rainfall is higher than the average for the grassland as a whole. They often extend along river valleys into the drier regions, forming galerias (*galeria* is the Italian for tunnel). In the driest areas the tall grasses give way to short grasses. There is a dry season, usually in winter and lasting up to four months. Average temperatures range from about 65°F (18°C) to more than 80°F (27°C).

Savanna (sometimes spelled savannah) grassland is found in all the tropical continents. Savanna grassland is bordered on one side by the humid TROPICS, at latitude 5–10°N and S, and on the other side by the subtropical deserts, at 15–20°N and S. The name "savanna" is derived from the Spanish *zavana,* which is believed to come from a word in the Carib language that was once spoken in parts of North America and the southern Caribbean. Savanna was originally the name for the tropical grasslands of Central and South America, but it spread to cover all such grasslands.

In the Thornthwaite classification, a semiarid climate is one with a moisture index between -67 and -33 and in which the potential evapotranspiration is less than 5.6 inches (less than 14.2 cm). The climate is designated D. In terms of thermal efficiency, this is a frost climate (E′).

In the Budyko classification, a semidesert climate is one in which the radiational index of dryness has a value of 2.0–3.0.

A steppe climate is one with a radiational index of dryness value of 1.0–2.0 in the Budyko classification

A taiga climate is typical of northern Russia, northern Scandinavia, northern Canada, and the interior of Alaska. These are the regions that support coniferous forest mixed with some broad-leaved species, especially birch (*Betula* species), alder (*Alnus* species), and willow (*Salix* species). This type of forest is known as boreal forest in North America and as taiga in Russia. Winters are long and cold and the hours of daylight are short. Summers are short and warm, with long hours of daylight. There is a large seasonal range in temperature. At Fairbanks, where the climate is typical of inland Alaska, the average July daytime temperature is 72°F (22°C) and the average January daytime temperature is -2°F (-19°C), a difference of 74°F (41°C). Verkhoyansk, Russia, has an even wider range, of 120°F (67°C), from a daytime average of 66°F (19°C) in July to -54°F (-48°C) in January. The climate is fairly dry and in winter the low temperatures mean that the ground is frozen, so water is not available for plants. Permafrost is found over much of the region, although it occurs in patches, discontinuously.

A temperate rainy climate occurs in middle latitudes. It corresponds to category Cf in the Köppen classification. Temperatures in the coldest month are between 26.6°F (-3°C) and 64.4°F (18°C) and in the warmest month temperatures are higher than 50°F (10°C). There is at least 2.4 inches (60 mm) of rain in the driest month.

A thermal climate is one that is defined only in terms of temperatures.

In the Strahler classification, a trade wind littoral climate is in Group 1, comprising climates controlled by equatorial and tropical air masses. Trade wind littoral climates are produced by maritime tropical air masses carried by the tropical easterly winds (the trades) from the western sides of oceanic subtropical regions of high pressure. They are found along narrow belts on eastern coasts in latitudes 10°–25° in both hemispheres. Temperatures remain fairly constant, and high, throughout the year. Rainfall is heavy, but with a strong seasonal variation. This type of climate is designated Af–Am in the Köppen classification.

A tree climate is any climate in which trees are able to grow. This includes all climates in which the mean summer temperature is at least 50°F (10°C) except for desert and some savanna and steppe climates that are too arid to support trees.

In the Strahler classification, a tropical desert and steppe climate is in Group 1, comprising climates controlled by equatorial and tropical air masses. This climate affects land areas in latitudes 15°–35° in both hemispheres and is associated with continental tropical air masses that develop in high-pressure cells in the upper troposphere (*see* ATMOSPHERIC STRUCTURE) above land areas lying on the tropics of Cancer and Capricorn. The climate is hot, with a moderate range of temperature over the year, and arid or semi-arid. This climate is designated BWh (desert) and BSh (steppe) in the Köppen classification.

A tropical monsoon climate is a warm, tropical climate with abundant rainfall that supports luxuriant rainforest vegetation, but that has a dry season in winter.

In the Strahler classification, a tropical wet-dry climate is in Group 1, comprising climates controlled by equatorial and tropical air masses. Tropical wet–dry climates occur in latitudes 5°–25° in both hemispheres. They are marked by a seasonal alternation between moist maritime tropical or maritime equatorial air and dry continental tropical air. This seasonal change produces a rainy season in summer and a dry season in winter. There are two types of tropical wet–dry climate: tropical rainy climate including the savanna climate, and the temperate rainy, or humid mesothermal, climate. These are designated Aw and Cwa respectively in the Köppen classification.

In the Budyko classification, a tundra climate is one with a radiational index of dryness of less than 0.33. In the Strahler classification, this climate is placed in Group 3, comprising climates controlled by polar and arctic air masses. A tundra climate occurs in latitudes north of 55°N and south of latitude 50°S along coasts exposed to frontal zones where maritime polar and continental polar air masses interact with arctic air masses to produce cyclonic (*see* CYCLONE) storms. The climate is moist and very cold, although the proximity of the ocean moderates temperatures, which are milder than those of an icecap climate. There is no summer or warm season. This is also designated a polar climate.

In the Strahler classification, a west-coast desert climate is placed in Group 1, comprising climates controlled by equatorial and tropical air masses. West-coast desert climates occur in latitudes 15°–30° in both hemispheres along narrow belts on western coasts that border the oceanic subtropical high-pressure cells. Stable, dry, maritime tropical air is subsiding in these cells. This produces a dry, fairly cool climate with a small range of temperature through the year and frequent FOG. In the Köppen classification this climate is designated BWk if it is cool and BWh if it is warm.

The kind of weather characteristic of middle latitudes, which is generated and transported by the prevailing westerlies is known as a westerly type. Weather conditions are variable, with successions of cyclones and anticyclones.

In the Strahler classification, a wet equatorial climate is placed in Group 1, comprising climates controlled by equatorial and tropical air masses. Wet equatorial climates are associated with warm, moist, tropical maritime air and equatorial air. These climates affect regions between latitudes 10°N and 10°S and also those parts of Asia in latitudes 10°–20°N that have a monsoon climate. Temperatures remain fairly constant throughout the year and rainfall is heavy, produced mainly by convectional storms. The wet equatorial climates include tropical rain forest climates, of which there are two types distinguished by whether or not they experience the monsoons. These are designated Af and Am in the Köppen classification.

climatic forcing A perturbation of the balance between the amount of energy that the Earth receives from the Sun and the amount that it reradiates back into space, that is imposed by some factor outside the climatic system but which produces climatic effects. A change in the output of solar energy would have such a climatic forcing effect, for example, as would a change in the concentration of atmospheric CARBON DIOXIDE (CO_2).

Climatic forcing is measured in watts per square meter (W/m^2). The forcing due to the increase in CO_2 since preindustrial times amounts to about 1.5 W/m^2. Calculating the forcing due to different factors is essential in predicting future climates.

Orbital forcing produces changes in climate as a consequence of variations in the ORBIT of the Earth around the Sun. This alters the intensity of the solar energy the Earth receives. The onset and ending of GLACIAL PERIODS are thought to be due to orbital forcing. *See* MILANKOVITCH CYCLES.

climatic normal The mean values for TEMPERATURE, HUMIDITY, and PRECIPITATION at a specified place over a fixed period. In many countries, including the United States, the fixed period is of 30 years and the period changes every 10 years. Recent fixed periods lasted from 1951 until 1980, 1961–1990, and 1971–2000. The use of a 30-year mean ensures that short-term variations in climate are hidden and the regular updating ensures that the data depict the present climate reasonably accurately.

climatic optimum A period during which the climates over most or all of the world are warmer than the climates before or after. The MEDIEVAL WARM PERIOD was a climatic optimum, but the warmest period since the end of the most recent ice age occurred between about 7,000 and 5,000 years ago. At that time, summer temperatures in Antarctica and in Europe were about 4–5°F (2–3°C) warmer than they are today. This postglacial optimum did not reach Greenland or the northern part of North America until about 4,000 years ago. As the ice melted, sea levels rose. The rise began about 17,000 years ago and by about 4,000 years ago sea levels may have been about 10 feet (3 m) higher than they are now.

climatic zone A region of the Earth, defined by latitude, within which the climate is sufficiently constant to be characteristic of the region as a whole. It was Aristotle (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) who introduced the concept of the climatic zone. He related the zones to changes in the length of daylight and called the zones *klimata,* from which we derive our word *climate*. Because latitude determines the height of the Sun above the horizon, measured in degrees, a type of climate defined in this way is also known as a mathematical climate.

Aristotle defined three *klimata*. The climatic belt closest to the equator was originally known as the winterless zone and later as the Torrid Zone. The high-latitude belts in each hemisphere were known as the summerless zones and later as the Frigid Zones. Separating the winterless and summerless zones there were the intermediate zones, later called the Temperate Zones. The boundaries separating the zones were the ARCTIC and ANTARCTIC CIRCLES and the tropics of Cancer and Capricorn.

Climatic zones form the basis for some modern schemes of CLIMATE CLASSIFICATION (*see*, for example, KÖPPEN CLIMATE CLASSIFICATION). The principal climatic zones that are accepted today include the high polar (80–90°N, 70–90°S), subpolar (60–80°N, 55–70°S), temperate (40–60°N, 35–55°S), subtropical wet (30–40°N, 30–35°S), subtropical dry (20–30°N and S), tropical seasonal (10–20°N, 5–20°S), and equatorial (10°N–5°S).

climatology The scientific study of climates. The word is derived from the Greek words *klima,* which means "slope," and *logos,* which means "account." The "slope" to which the name refers is the inclination of the Earth's axis of rotation to the PLANE OF THE ECLIPTIC (*see* AXIAL TILT). Although this inclination does not produce climates, it does produce the SEASONS, and the ancient Greeks noticed the connection (*see* Aristotle in APPENDIX I: BIOGRAPHICAL ENTRIES). Climatology encompasses every aspect of the physical state of the atmosphere over particular parts of the world and over extended periods of time.

Climatologists also attempt to estimate what the climates of the world will be like in years to come. They build CLIMATE MODELS to help them. Calculations of future GLOBAL WARMING are derived from climate models developed by climatologists.

There are also climatologists who specialize in the reconstruction of past climates. Their discipline is called paleoclimatology, and one of the techniques available to paleoclimatologists involves the study of TREE RINGS and is known as dendroclimatology. Dendroclimatologists estimate the growing conditions experienced by the trees during the past and from that attempt to reconstruct details of the climate in which the trees grew.

The movements of AIR MASSES and of the air within them comprise dynamic climatology, which is the scientific study of the movements of air and of the thermodynamic processes that cause them. The term was coined in 1929 by Tor Bergeron (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) to describe the way the concept of air masses and fronts might be developed.

Synoptic climatology deals with the influence of atmospheric circulation patterns on regional climates. It is concerned with regional climates up to the scale of a hemisphere, but not with global climates. Studies of ENSO events are classed as synoptic climatology. Air mass climatology is a type of synoptic climatology in which the weather characteristic of a region is related to the characteristics of the air masses that affect it and the length of time each type of air mass remains over the region.

The climates of particular regions are the subject of regional climatology. Regional climatology involves CLIMATE CLASSIFICATION, the purpose of which is to facilitate comparisons between climates.

The scale of their subject matter also distinguishes branches of climatology. There are three such branches, called macroclimatology, mesoclimatology, and microclimatology in decreasing order of scale. Cryptoclimatology, which is the climatology of enclosed spaces, is a branch of microclimatology.

Descriptive climatology is climatology presented as descriptions of climates, using verbal accounts, graphs, tables, and other illustrations, but omitting discussions of the causes of climatological phenomena or of climatological theory.

Physical climatology is the branch of climatology that deals with exchanges of mass and energy in the troposphere (*see* ATMOSPHERIC STRUCTURE), that is to say with the physical processes that produce and regulate climate. This is contrasted with dynamic climatology, which is concerned with motion and dynamic processes, and synoptic climatology, which relates the circulation of the atmosphere to the differences in climates. Physical climatologists study the amount of solar radiation received at a particular place and the processes by which it is converted into other forms of energy, such as KINETIC ENERGY and chemical energy, and finally returned to space as infrared radiation (*see* SOLAR SPECTRUM). Many of these processes involve the CONDENSATION, EVAPORATION, DEPOSITION, and SUBLIMATION of water, and it is the absorption of solar energy that drives the HYDROLOGICAL CYCLE. All of these responses of water to the gain and loss of energy are central to physical climatology. The study of URBAN CLIMATES also forms an increasingly important part of physical climatology.

The use of recorded RADAR echoes showing clouds and precipitation in studies of the climate comprises a method known as radar climatology. If the records extend over several decades, they can reveal any pattern that exists in the distribution of cloud and precipitation over a particular region. This information is then incorporated into the overall picture, or model, of the climate of that region.

Climate studies are directly relevant to a variety of everyday activities. Housing developments must take account of the climates in which people will live, and architects must design buildings accordingly. Climatologists also contribute to the planning of the use of natural resources, and the study of the effect of climate on farming is so important that it forms a branch of the overall discipline called agroclimatology.

Applied climatology involves the use of climatological information and concepts to help in solving economic, social, and environmental problems. In some cases, the climatological contribution is so great that it has generated a scientific specialism. The application of climatological studies to agricultural planning, for example, produced agroclimatology. An understanding of climate is also relevant to fisheries, the management of water resources, energy requirements (the length and severity of winters), the design of buildings, pollution control, aviation, and many other areas of life.

Industrial climatology is the application of climatological studies to industry in order to determine the influence of the climate on a particular industrial operation. If the industry imports materials or exports products by sea, for example, its proximity to a port that remains ice-free in winter is likely to be important. The direction of the prevailing wind (*see* WIND SYSTEMS) indicates areas that will be most affected by factory emissions. Extreme temperatures make certain operations difficult. Chocolate factories sometimes close in very hot weather, because the molten chocolate will not set, and so it is important for the factories to be located in places where summer heat waves are uncommon. These are among the climatological factors industrial planners must take into account when alternative sites for a new factory are being considered.

Bioclimatology is the branch of climatology devoted to the scientific study of the relationship between living organisms and the climates in which they live. Bioclimatology is a branch of biogeography, which is the study of the geographic distribution of plants and animals.

Bioclimatic zones are distributed by latitude and distance from the ocean, and they also exist on a smaller scale. A mountain, for example, has a number of distinct climates, each supporting its own community of organisms. At sea level, tropical rain forest covers the Andes of central Peru. This gives way to a more open type of forest at an elevation of about 3,300 feet (1,000 m) and to a still more open type in which the trees are smaller and covered in mosses and lichens, called montane forest, at about 6,600 feet (2,000 m). Above about 9,800 feet (3,000 m) the trees are smaller still. This is called elfin woodland. Beyond the elfin woodland, above about 13,000 feet (4,000 m), there is grassland, and above about 16,400 feet (5,000 m) the vegetation becomes increasingly sparse. There is continuous snow and ice above 19,700 feet (6,000 m). Mountains in other parts of the world are divided into similar altitudinal zones, but these vary in detail from one mountain range to another. Bioclimatology involves the study of climatic zones such as these and of the organisms that inhabit them. It also includes more specialist subdisciplines, such as agroclimatology.

Phytoclimatology is the scientific study of the climatic conditions in the air between and adjacent to growing plants and on the surfaces of plants.

An observing station where meteorological data are collected and stored over a long period for use in climatological studies is known as a climatological station. The climatological station elevation is the datum level that is used as a reference for all records of AIR PRESSURE in a particular region. It is the vertical height above sea level of an identified point at a climatological station. The air pressure that is calculated for the climatological station elevation is called the climatological station pressure. Its use allows all climate records to be compared, because they all refer to the same height above sea level. The climatological station pressure may differ from the station pressure (*see* STATION MODEL).

Paleoclimatology is the scientific study of the climates that existed in the distant past. The *paleo* in the name is derived from the Greek *palaios,* which means "ancient."

By reconstructing past climates, paleoclimatologists provide a background against which the history of the Earth can be seen. Knowledge of paleoclimates helps geologists, botanists, zoologists, and ecologists to understand how particular regions of the world developed to the conditions in which we see them today. They are able to explain how it is that animals and plants once lived in places they would now find intolerable, such as the hippopotamuses and tropical lotuses that once lived in the center of London.

Paleoclimatologists also provide important information about climate itself. We know from their researches that about 20,000 years ago—a very short time in geological terms—the Northern Hemisphere lay in the grip of the coldest part of an ice age known as the Wisconsinian (Devensian) GLACIAL PERIOD. At that time sheets of ice thousands of feet thick covered much of North America and Eurasia, and where the bare ground was exposed it was frozen to a considerable depth. We also know that at other times the world has been much warmer than it is today. The paleoclimatological record shows the extremes of climate that are possible.

These studies are relevant to modern concerns. By describing past conditions, they provide suggestions of what the world might be like if its climates were to become markedly warmer or colder and just how warm or cold they are capable of becoming. They provide warnings of the kind of surprises climate change may bring, like the sudden drop in temperatures almost to ice-age levels that interrupted the rapid warming at the end of the most recent ice age (*see* YOUNGER DRYAS). This change is believed to have been due to one of several HEINRICH EVENTS, which suppress the formation of NORTH ATLANTIC DEEP WATER and partially or completely shut down the GREAT CONVEYOR. There were also sudden and dramatic rises in temperature during ice ages, known as DANSGAARD–OESCHGER EVENTS.

Obviously, there are no written records of ancient climates. Paleoclimatologists must study indirect evidence in order to discover the causes that produced observable effects. Many lines of inquiry are open to them.

Wind, rain, and repeated freezing and thawing leave clear marks on rocks and on landscapes. Traces of sand dunes often survive for many thousands of years after the desert in which they formed has vanished. Rivers leave behind gravel from which their size and courses can be tracked. Soil that is made from loess (wind-blown DUST) indicates a dry climate in which the winds are dusty, and the dust itself can often be traced to the rocks that were eroded to produce it. This reveals the direction of the prevailing wind (*see* WIND SYSTEMS), which in turn reveals the kind of weather patterns that predominated at the time. That time can be calculated, for example by the RADIOCARBON DATING of organic material present in the undisturbed soil.

Plants and animals tend to be associated with particular climates and both leave traces. Plants leave POLLEN or SPORES from which the type of plant, and sometimes even the species, can be identified. Animals leave identifiable teeth and fragments of bone, and beetles, some species of which tolerate only a narrow range of temperature, leave behind their wing cases, or elytra (*see* BEETLE ANALYSIS). Groups of plants and animals, called assemblages, give a clear indication of the weather conditions at the time and place where they lived together.

Purely physical changes also leave clues in the form of changes in OXYGEN isotope ratios. These can be related to rising or falling temperature. Dust trapped in ice sheets and extracted from ICE CORES indicates whether climates were generally dry or wet, because the air contains more dust in dry weather than it does in wet weather.

Paleoclimatologists are building a fairly detailed history of the world's climate that extends about 100,000 years into the past. Still farther back in time they have "snapshot" pictures of conditions at particular times. Obviously the weather would have varied from year to year, but the snapshots probably represent the general kind of weather that was typical over long periods.

cloud A large concentration of liquid water droplets or ICE CRYSTALS that form by the CONDENSATION of WATER VAPOR in SATURATED AIR and that remain suspended in the air, clear of the surface. At any time about half the surface of the Earth is covered by clouds.

CLOUD DROPLETS and ice crystals range in size from less than 1 μm to about 50 μm (less than 0.0004–0.02 inch). CLOUD CONDENSATION NUCLEI must be present in order for water to condense out of saturated air. Inside a cloud, individual droplets and crystals usually survive for less than one hour before evaporating or sublimating (*see* SUBLIMATION). Newly condensed droplets and newly frozen crystals immediately replace them. Close examination (using binoculars) of the edges of a CUMULIFORM cloud reveals what is happening. Fibers of cloud are constantly twisting away from the main mass and dissipating, but the cloud as a whole remains the same size or grows bigger. Cumuliform clouds are short-lived. It may take no more than half an hour for a small cloud to grow into a cumulonimbus storm cloud (*see* CLOUD TYPES) that extends all the way to the tropopause (*see* ATMOSPHERIC STRUCTURE), and an hour later that cloud may have dissipated completely. The ephemeral nature of such clouds is due to the fact that they form as isolated units in unsaturated air. Once liquid droplets and snowflakes falling from the top of the cloud chill the rising warm air that sustains them, CONVECTION ceases and the cloud quickly evaporates into the surrounding air. Stratiform clouds form in stable air (*see* STABILITY OF AIR) and strong convection plays no part in their formation. Consequently, they last longer. Some can survive for a week or more, but even they do so by constant evaporation and condensation. It takes an individual PARCEL OF AIR inside a stratiform cloud little more than one day to emerge into drier air where its droplets evaporate.

There are many types of cloud, distinguished from one another by their shape and the manner in which they form. This variety of cloud forms is described by an internationally accepted system of CLOUD CLASSIFICATION.

The upper surface of a cloud layer is called the cloud deck.

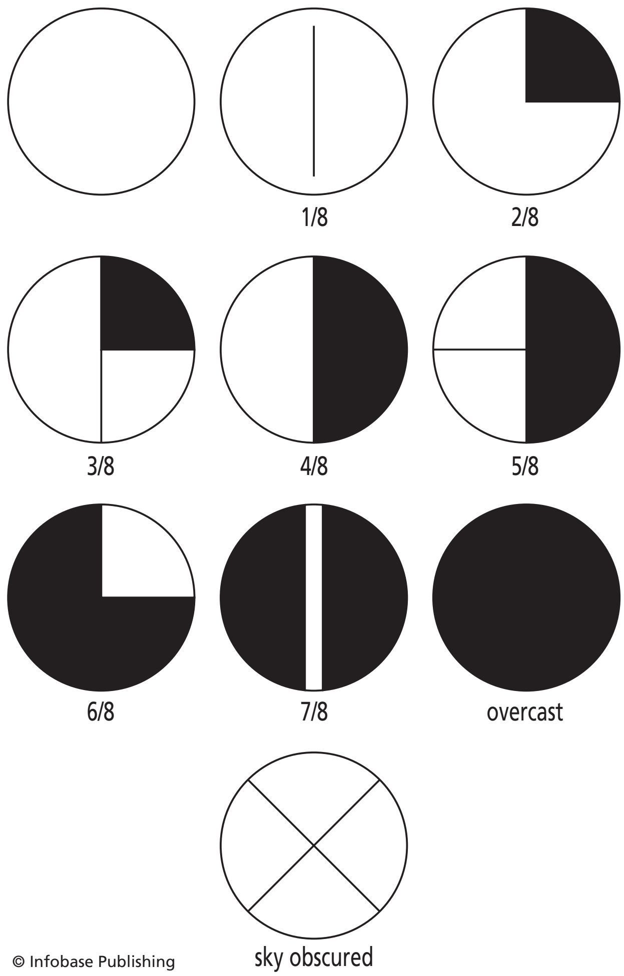
A linear formation of clouds that is 10–100 miles (16–160 km) wide and varies in length from tens to hundreds of miles is known as a cloud band. Spiral cloud bands are sometimes seen under the strongly BAROCLINIC conditions found behind an active cold FRONT.

A cloud bank is a well-defined mass of cloud that is seen from a distance. It extends across most of the horizon but does not cover the sky directly overhead.

A cloud bar is a long, narrow, horizontal cloud that is clearly defined. It may be an element of a system of billow clouds or a lenticular cloud. A cloud bar may also appear as a dark cloud bank on the horizon that is the outermost edge of the clouds associated with a tropical CYCLONE, and that heralds the approach of the storm.

cloud amount The extent to which the sky is obscured by cloud, also known as the amount of sky cover. This information is included in reports from WEATHER STATIONS together with details of the CLOUD TYPE. A full description of the sky that includes the amount, type, and height of all the clouds and the direction in which they are moving is called the state of the sky.

Cloud amount is measured from a reflection of the sky in a mirror marked with grid lines dividing it into equal areas, or by a nephometer. This is an instrument comprising six mirrors, one at the center surrounded by five radiating from it. The observer counts the number of areas that are filled with cloud, or estimates the proportion of the sky that is covered by cloud.



Shading of the station circle indicates the proportion of the sky that is covered by cloud. There are 10 possibilities. An open circle indicates no cloud; a fully shaded circle indicates complete cloud cover; a diagonal cross indicates that the sky is obscured; and the remaining symbols represent proportions from one-eighth to seven-eighths; these can also be interpreted in tenths.

The total cloud amount is reported in tenths or in eighths, known as oktas, and it is indicated on a STATION MODEL by shading on the station circle. The clouds may be partly transparent, so the sky is not completely hidden, and they may extend all the way to the ground. The proportion is expressed in tenths or oktas. Symbols for cloud amount are in oktas, but these can be interpreted in tenths as: 1/8 = 1/10 or less; 2/8 = 2/10-3/10; 3/8 = 4/10; 4/8 = 5/10; 5/8 = 6/10; 6/8 = 7/10–8/10; 7/8 = 9/10 or overcast but with gaps in the cloud cover.

In United States practice, the summation principle is used to report the sky cover at any specified level. The principle is that the sky cover is equal to the total sky cover at each cloud layer from the lowest to the level specified. This means that at no level can the cloud cover be less than the cover at lower levels and the total cloud cover cannot exceed 10/10 (or 8 oktas).

The sky is overcast when a layer of cloud covers all or most of it. In reporting weather conditions, the sky is said to be overcast when at least 95 percent or 7 oktas of the sky is covered by cloud. An undercast sky is one blanketed by a complete cloud cover (ten tenths or 8 oktas) as it appears to, and is reported by, the pilot of an aircraft flying above the cloud.

The sky is not overcast if it is covered by an obscuring phenomenon, which is any atmospheric feature, other than clouds, that obscures a portion of the sky as seen from a weather station. The sky is then said to be obscured. Partial obscuration is the condition of the sky when part of it, up to 90 percent or 7 oktas, is hidden by an obscuring phenomenon on the surface. The proportion of the sky that is covered by cloud that does not completely hide whatever may be above it is called the transparent sky cover. Higher clouds or blue sky can be seen through the layer of cloud. The proportion of the sky that is covered by cloud that completely hides anything that might be above it is known as the amount of *opaque sky cover.* The amount is usually expressed in tenths of the total sky. Partial obscuration, obscuring phenomenon, opaque sky cover, and transparent sky cover are terms used in United States meteorological practice.

When clouds are present but for most of the time they cover less than the whole sky, the condition is described as being partly cloudy. In reporting weather conditions, the term is used rather more precisely to indicate that over a period of 24 hours the average cloud cover has been 1–4 oktas (between 10 percent and 50 percent). Scattered cloud is cloud that covers up to half of the sky (4 oktas).

The condition in which more than 90 percent but less than 100 percent of the sky is covered by cloud is called breaks in overcast. If between 60 percent and 90 percent of the sky is covered by cloud, the cloud cover is said to be broken. The sky is clear when cloud covers less than one-tenth of the sky. Used as a verb, the sky is said to clear when cloud dissipates, ending PRECIPITATION and leaving the sky largely cloudless. In a cloudy sky, cloud covers more than 6 oktas or 70 percent of the sky, and the sky remains covered by cloud for at least 24 hours.

An emissary sky is one covered by patchy cirrus cloud. This type of cloud often forms in humid air on a warm FRONT. Its appearance indicates the approach of weather associated with the lower part of the front, so the cloud acts as an emissary of the rain and winds that are to come.

cloud base The height of the lowest part of an individual cloud or a layer of cloud, measured as the distance above sea level. Sea level is used as a datum because it is constant. Heights measured above ground level vary according to the surface topography, so although they would indicate the height of the cloud above the ground at a particular place, they could not be used reliably for any other place. The vertical distance between the surface and the cloud base is also called the cloud height.

Some or all of the air that lies below the cloud base is known as the subcloud layer. The term is sometimes used to describe all the air between the cloud base and the surface. At other times it describes the shallow layer of stable air that occurs beneath the base of clouds produced by CONVECTION.

Clouds are classified according to their bases as high, medium, and low, even though some, such as cumulonimbus (*see* CLOUD TYPES), may extend to a great height; the three groups are called cloud levels (*see* CLOUD CLASSIFICATION). A cloud layer comprises stratiform clouds or a number of clouds of the same or different types that cover all or part of the sky and have a cloud base at approximately the same height everywhere. Cloud layers can occur at different levels, one above the other, with clear air between them.

The ceiling is the height ascribed to the lowest layer of clouds or of anything else obscuring the sky, when the sky cover (*see* CLOUD AMOUNT) is described as broken, overcast, or obscured, and the cover is not classified as thin or partial. If the cloud cover is thin or partial, the ceiling is said to be unlimited. A variable ceiling is one that changes in height rapidly and repeatedly while its height is being measured. The height of the ceiling must then be given as the average of the measured values. Variable ceilings are reported only if their height is lower than 3,000 feet (915 m).

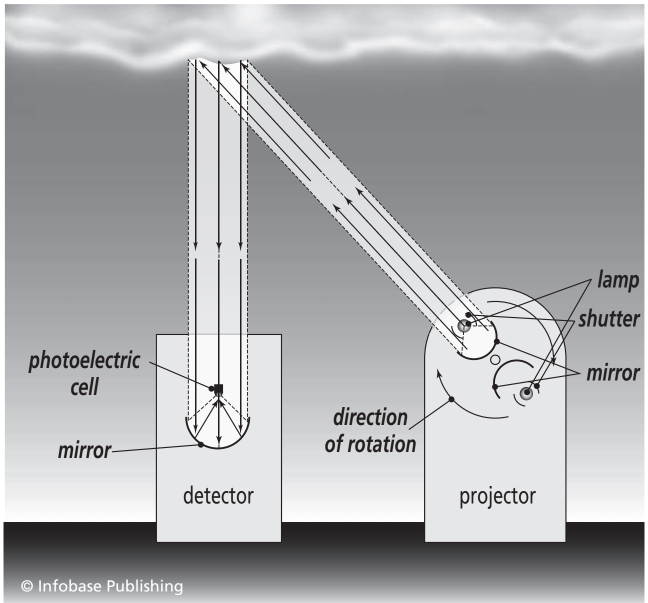
The emergence of a mass of cloud beneath the base of a large cumulonimbus cloud is called lowering. The effect is to lower the cloud base. Distinct rotational and vertical movement is sometimes visible in the lowered cloud. This is caused by air being drawn into the base of the main cloud, and it indicates that the storm has become tornadic (*see* TORNADO).

The ceiling classification is a description of the way the ceiling was determined. It is included in weather reports for airports as a letter preceding the ceiling height. A means the ceiling was measured by an airplane, B means it was measured by a balloon, E that it was estimated, M that it was measured, P that there is precipitation, W that the ceiling is indefinite, and V that it is variable. A25 would mean an airplane had measured the height of the ceiling at 2,500 feet (762.5 m).

The height of the cloud base is known as the aircraft ceiling when it has been measured by the pilot of an aircraft flying within 1.5 nautical miles (1.725 miles, 2.78 km) of the runway of the airport to which the ceiling refers. Airfield controllers often ask pilots to report the cloud ceiling in the vicinity of the field. (Its ceiling is also the greatest altitude to which a particular type of aircraft is capable of climbing.) If the ceiling is determined by timing the ascent and disappearance of a balloon it is called the balloon ceiling.

The cloud base is often measured by means of a ceiling light, also known as a cloud searchlight. This is a small searchlight that projects a narrow beam of light, spreading by less than 3°, vertically upward onto the base of a dark cloud or onto a cloud base at night. The light illuminates a spot on the cloud. An observer positioned a measured distance between 500 feet and 1,000 feet (150–300 m) from the ceiling light measures the elevation of the spot. The height of the cloud base (h) is then calculated by trigonometry: $h = a\tan\theta$, where a is the distance between the ceiling light and the observer and θ is the angle of elevation. This method has been used to measure the height of clouds up to 15,000 feet (4,575 m) with an accuracy of about 2,500 feet (750 m).

Alternatively, the ceilometer is a device that can be used in daylight, when the sky is very much brighter than the area illuminated by a searchlight. The ceilometer consists of two lamps, focused by parabolic mirrors, that each shine through a shutter, which restricts the width of the beam. The mirrors, with the shuttered lamps above them, are arranged back-to-back, and they rotate at a given rate so that the beam is transmitted as a series of pulses. The beams shine at an angle onto the base of the cloud. A detector, positioned some distance away, consists of a photoelectric cell attached to electronic filters that allow it to respond only to a series



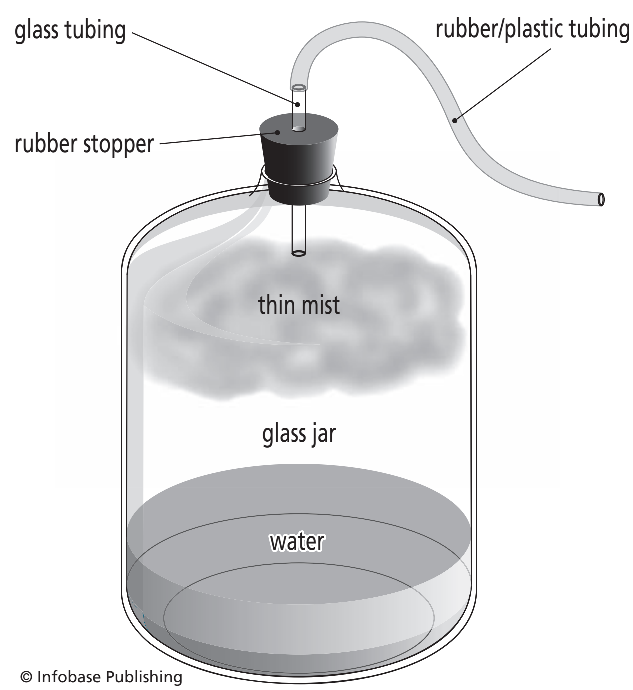
A ceilometer shines a beam of light, pulsating at a predetermined frequency, onto the cloud base. A detector contains a photoelectric cell that will respond only to a signal at that frequency.

of pulses at the predetermined frequency. The height of the cloud base is then calculated by trigonometry from the angles of the transmitted and reflected beams and the known distance between the projector and the detector. The signal from the photoelectric cell is then amplified. A ceilometer can measure cloud bases up to 10,000 feet (3,000 m) during the day and up to about 20,000 feet (6,000 m) at night.

cloud chamber A device that is used to study CLOUD FORMATION and also to detect the tracks of particles carrying an electric charge. It was invented in 1896 by the Scottish physicist Charles Thomson Rees Wilson (1869–1959), who worked at the Cavendish Laboratory of the University of Cambridge, England, and was especially interested in the way clouds form. Wilson shared (with Arthur Compton, 1892–1962) the 1927 Nobel Prize in Physics for this discovery.

Between 1895 and 1899 Wilson showed that CLOUD DROPLETS can form in the absence of CLOUD CONDENSATION NUCLEI if the air is supersaturated (*see* HUMIDITY) and that droplets form more readily in very clean air if the air is exposed to X-rays. This demonstrated that the droplets condense onto ionized (*see* ION) water molecules. In 1946, Vincent Joseph Schaefer and Bernard Vonnegut (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) used a cloud chamber to perform the experiments that led to techniques for CLOUD SEEDING.

There is a simple home demonstration that shows how cloud forms when a sharp drop in AIR PRESSURE reduces the temperature of moist air below its dew point temperature (*see* DEW). Anyone wishing to make a small cloud chamber will need a glass bottle that holds about one gallon (3.8 l), a stopper that will seal the bottle tightly, glass tubing, rubber or plastic tubing, and a strong source of light such as a slide projector. The stopper should be pierced by a hole that is just big enough for the glass tubing to fit snugly. There should be about two inches (5 cm) of water in the bottom of the bottle. The apparatus is assembled by inserting the stopper with the glass tubing through it. The rubber or plastic tubing should be attached to the other end of the glass tubing and the bottle shaken vigorously. This ensures that the air and water in the bottle are at the same temperature throughout. The demonstrator should blow hard into the rubber or plastic tubing, then hold the tube tightly shut between the finger and thumb. Blowing into the bottle increases the air pres-



Blowing through the tube into the bottle increases the internal pressure. When the pressure is released, the air cools adiabatically and cloud forms.

sure inside. Keeping the tube sealed, the bottle should be shaken again. This ensures that the air in the bottle is saturated. The bottle should then be placed so the light is shining into it. Watching carefully, the demonstrator then releases the tube. The pressure inside the bottle will drop suddenly as it equalizes with the air pressure outside. This cools the air adiabatically (*see* ADIABAT) and a thin mist will form inside the bottle. The mist is thin only because the cloud chamber is so small. If this happened on a large scale it would produce a big, dense cloud.

cloud classification Clouds vary greatly in color and shape and they form at different heights above the surface. Throughout history people have sought to standardize the way in which clouds are described, so that a person in one place could send an unambiguous account of the appearance of the sky to someone who has not seen it. This is more difficult than it may seem. The Greek philosopher Theophrastus (371 or 370–288 or 287 B.C.E.) attempted to do so, but could do no better than "clouds like fleeces of wool" and "streaks of cloud." If Theophrastus were to tell a friend in a far country that he had seen "streaks of cloud" the friend would be little the wiser, because this might describe several quite different kinds of cloud.

Chevalier de Lamarck (1744–1829) also tried. Lamarck (his full name was Jean-Baptiste-Pierre-Antoine de Monet) was primarily a biologist, but one who specialized in classification, so classifying clouds must have seemed a similar task. He devised six categories. These were colorful, but somewhat vague: cloud sweepings; clouds in bars; dappled clouds; grouped or piled clouds; veiled clouds; and clouds in flocks.

Success finally came in 1803, when Luke Howard (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) proposed a system that is the basis of the one in use today. In 1895, the International Meteorological Committee expanded the Howard system and the resulting classification was revised several times before being adopted officially for use in the *INTERNATIONAL CLOUD ATLAS*.

In the modern system, clouds are classified first according to the height of the CLOUD BASE, as high, middle, and low. This division is made mainly for convenience and it refers to the height at which the bases of clouds most commonly occur. They are not confined to these bands, however.

Then clouds are divided according to their appearance into 10 basic types, or genera, with names based on the Latin names cirrus, cumulus, and stratus introduced by Howard. These mean "hair," "pile," and "layer" (from *stratum*) respectively. This results in:

Cumulus and cumulonimbus clouds sometimes extend vertically to a considerable height. They are usually classified as low clouds by the height of their bases.

The nine basic types are further divided into 14 species: calvus, capillatus, castellanus, congestus, fibratus, floccus, fractus, humilis, lenticularis, mediocris, nebulosus, spissatus, stratiformis, and uncinus.

There are also nine varieties: duplicatus, intortus, lacunosus, opacus, perlucidus, radiatus, translucidus, undulatus, and vertebratus.

Clouds may also possess accessory clouds such as pileus, tuba, and velum, and supplementary features such as arcus, incus, mamma, praecipitatio, and virga.

An accessory cloud is a small cloud that is seen in association with a much larger cloud belonging to one of the cloud genera.

Cloud Level	Height of Base					
	Polar Regions		Temperate Latitudes		Tropics	
	'000 feet	*'000 meters*	*'000 feet*	*'000 meters*	*'000 feet*	*'000 meters*
High cloud:	10–26	3–8	16–43	5–13	16–59	5–18
Types: cirrus, cirrostratus, cirrocumulus						
Middle cloud:	6.5–13	2–4	6.5–23	2–7	6.5–26	2–8
Types: altocumulus, altostratus, nimbostratus						
Low cloud:	0–6.5	0–2	0–6.5	0–2	0–6.5	0–2
Types: stratus, stratocumulus, cumulus, cumulonimbus						

cloud condensation nuclei (CCN) Small particles that are carried by the air and onto which water vapor condenses, the resulting droplets forming clouds. In very clean air it is possible for the relative HUMIDITY to exceed 100 percent without water vapor condensing; the air is then supersaturated. This is because water vapor condenses readily onto a surface, but condenses only with difficulty if there is nothing on which droplets can form. Water vapor easily condenses onto plant surfaces as DEW, and onto windows and other solid surfaces. In the air it condenses onto airborne particles—cloud condensation nuclei.

Airborne particles vary greatly in size, although all of them are microscopically small. Water does not condense onto the smallest particles, with diameters of about 0.002 µm. This is because the SATURATION VAPOR PRESSURE is higher over a curved water surface than it is over a flat one, and it increases as the curvature increases. This is known as the curvature effect, and it arises because the force that binds water molecules to each other is strongest on a flat surface and weakens as curvature of the surface increases. Consequently, water evaporates much faster from a curved surface than from a flat one and small droplets evaporate much faster than big ones. Droplets that form on the smallest particles evaporate almost instantly.

Giant particles, more than 20 µm across, are so big they do not remain airborne long enough for water to condense onto them. The most effective particles are those between 0.2 µm and 2.0 µm in diameter. Air over land contains an average of about 80,000 to 100,000 of such cloud condensation nuclei in every cubic inch (5–6 million per liter) and air over the ocean, far from the nearest land, usually contains about 16,000 per cubic inch (1 million per liter).

As the relative humidity rises the hygroscopic nuclei are affected first. A hygroscopic nucleus possesses the property of wettability, meaning that its surface has an affinity for water, so water spreads across it. Being hygroscopic means the particle is made from a substance that absorbs water and swells in size as it does so, and that eventually it dissolves into a concentrated solution. Common salt (sodium chloride, NaCl) is hygroscopic. Crystals of salt that are left exposed to the air will gradually clump together and eventually turn into a solution, using water they have absorbed from the air. Salt crystals occur naturally in the air over the sea. They remain airborne after the water has evaporated from drops of seawater that are thrown into the air as spray. Other naturally occurring hygroscopic nuclei include particles of dust, smoke, sulfate (SO_4), and sulfur dioxide (SO_2). Water can start forming droplets around salt crystals when the relative humidity reaches 78 percent and the other hygroscopic nuclei absorb water at somewhat higher humidity. When the relative humidity reaches about 90 percent, enough vapor may have condensed to form a fine haze that restricts visibility.

Hygroscopic nuclei dissolve in the water they absorb. This leads to the solute effect. The droplets are not of pure water, but are solutions, and the saturation vapor pressure over any solution is lower than that over a surface of pure water. The smaller the droplet, the more concentrated the solution—because the hygroscopic nucleus has dissolved in less water—and the stronger the solute effect. It is because of the solute effect that the first droplets to form are very small and condense onto hygroscopic nuclei. As the relative humidity continues to rise, other nuclei become active, including the larger among the nonhygroscopic particles.

A mixed nucleus is a cloud condensation nucleus that has formed by coagulation from material of two different types. One substance is hygroscopic and the other is nonhygroscopic, but may possess the property of wettability. The efficacy of a mixed nucleus is inferior to that of a hygroscopic nucleus and superior to that of a nonwettable particle.

A combustion nucleus is a cloud condensation nucleus that was released by COMBUSTION, such as a particle of ash, or condensed from a gas released as a product of combustion, such as sulfate (SO_4) formed by the oxidation of SULFUR DIOXIDE (SO_2). Most combustion nuclei are hygroscopic.

Over the open ocean the most abundant condensation nuclei consist of dimethyl sulfide (DMS). This is a chemical compound, $(CH_3)_2S$, produced by the decomposition of dimethylsulfonio propionate, a substance present in the cells of many single-celled marine algae, where it prevents the salt concentration from rising to a harmful level. When the organisms die, the dimethylsulfonio propionate decomposes and DMS enters the water, where its decomposition continues. A proportion of the DMS escapes into the air, however, where it is rapidly oxidized. One product of DMS oxidation is sulfuric acid (H_2SO_4). Small droplets of H_2SO_4 form ideal cloud condensation nuclei. DMS is also the most important compound involved in the transport of sulfur from the sea to the land as part of the SULFUR CYCLE. High levels of DMS have been detected in air over the Great Barrier Reef, and it is now known that the Reef is an important static source of DMS.

More water then condenses onto the droplets, increasing their size. This reduces the solute effect by weakening the solution, but at the same time it also reduces the curvature effect. Before long, water vapor is condensing so rapidly that the relative humidity of the air between droplets starts falling. Air adjacent to droplets is no longer supersaturated. Once the relative humidity falls to 100 percent, no more nuclei are activated. The result is to produce droplets of a size that is in equilibrium with the amount of water in the cloud. Supersaturation rarely exceeds 101 percent.

Cloud condensation nuclei are removed from the air by rainout. Water vapor condenses onto the particles and the resulting CLOUD DROPLETS grow in size until they fall as precipitation, carrying the solid particles with them. Particles are also removed from the air by FALLOUT, impaction (*see* AIR POLLUTION, and washout (*see* RAINDROPS).

The Aitken nuclei counter is a laboratory device, invented by John Aitken (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), that is used for estimating the concentration of cloud condensation nuclei in a sample of air. The sample of air is drawn into a chamber where it is kept near saturation by the presence of sodden filter paper. A pump then makes the air expand rapidly. The expansion causes it to cool. Water droplets condense onto the nuclei present in the air, and some fall as a shower onto a graduated disk. A lens makes the droplets clearly visible, allowing them to be counted. Each droplet is assumed to represent one condensation nucleus.

cloud droplet A particle of liquid water that is held in suspension inside a CLOUD. A liquid cloud droplet is also known as a cloud particle, a term that also describes an ICE CRYSTAL which forms part of a cloud.

Cloud droplets range in size from less than 0.00004 inch to 0.002 inch (less than 1 μm to about 50 μm), and usually they survive for less than one hour before they evaporate. Clouds last for much longer than one hour because new droplets form as fast as cloud droplets evaporate.

The size of cloud droplets varies according to the size of the CLOUD CONDENSATION NUCLEI onto which the water vapor has condensed. A typical cloud droplet is about 0.0004 inch (10 μm) in diameter, there are about 283 of them in every cubic foot of air (100,000 per liter). Average-size droplets fall at about 0.4 inch per second (1 cm/s). Big cloud droplets are about 0.002 inch (50 μm) across, there are about 3 of them in every cubic foot of air (1,000 per liter), and they fall at about 11 inches per second (27 cm/s).

Cloud droplets merge to form RAINDROPS by coalescence, or by the Bergeron-Findeisen mechanism. By the time it falls from the cloud, a single raindrop consists of approximately 1 million cloud droplets. In a warm cloud (*see* CLOUD TYPES), droplets also grow by a process called the Reynolds effect that was discovered by Osborne Reynolds (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). The Reynolds effect occurs in a cloud where some droplets are warmer than others; water evaporates from the warmer droplets and condenses onto the cooler droplets.

cloud formation An expression that has two meanings. It can be a particular pattern of CLOUDS with particular shapes—a formation of clouds. More usually, it refers to the processes by which clouds form.

When air rises, its TEMPERATURE decreases adiabatically (*see* ADIABAT) and when it subsides, its temperature increases adiabatically. Air can also be chilled or warmed by mixing with air at a different temperature. The amount of WATER VAPOR a given volume of air can contain depends on the temperature of the air: Warm air can hold more water vapor than cold air. Consequently, as air rises and its temperature falls, or as it mixes with cooler air, its relative HUMIDITY (RH) increases. When its RH approaches 100 percent, water vapor will begin to condense onto CLOUD CONDENSATION NUCLEI. The height at which rising air reaches its dew point temperature (*see* DEW) is called the lifting condensation level (*see* CONDENSATION).

Immediately after air reaches its lifting condensation level, water vapor starts to condense into minute droplets. Cloud begins to form in a matter of a few seconds. Condensation releases LATENT HEAT. The released latent heat warms the air around the water droplets, causing the air to continue rising and cooling, and further cooling leads to further condensation. The process ends when enough water vapor has been removed from the air for the dew point temperature to rise above the ambient air temperature. The level at which this occurs marks the top of the cloud.

cloud physics A branch of physics that is concerned with the scientific study of the physical properties and behavior of CLOUDS. It includes CONDENSATION and the other processes involved in CLOUD FORMATION; the formation of RAINDROPS, hailstones (*see* HAIL), and SNOWFLAKES that fall as PRECIPITATION; the radiative properties of clouds, such as their ALBEDO and their absorption and emission of infrared radiation (*see* SOLAR SPECTRUM); and the transport of energy inside clouds. CLOUD DROPLETS grow into raindrops by collision and coalescence, but if the cloud also contains ICE CRYSTALS raindrops may form by the Bergeron-Findeisen mechanism. Electric charge may separate inside large cumulonimbus clouds (*see* CLOUD TYPES), and a cloud in which this happens may give rise to a THUNDERSTORM. These electrical processes also form part of the subject matter of cloud physics.

cloud seeding Injecting material into supersaturated air (*see* HUMIDITY) in order to make water vapor condense into CLOUD DROPLETS or ICE CRYSTALS. The technique is used to make rain fall where otherwise it might not have fallen, and also to protect farm crops by inhibiting the formation of HAIL.

The advantages of reducing hail damage and of making rain fall where and when it is needed are obvious. For thousands of years people have dreamed of being able to control the weather in this way, but it was not until 1946 that scientists studying a different problem came across a way to do it.

There had been earlier attempts. In 1891, the United States Congress appropriated $9,000 for experiments in which cannons were fired into clouds and explosives were detonated inside low clouds from kites and balloons. The purpose of the experiments was to check whether there was any truth in an old story that rain often fell after a major Civil War battle—the story proved to be unfounded. Large, muzzle-loading mortars were also fired vertically upward into clouds to prevent hail formation. By 1899, thousands of such "hail cannons" were in use in Europe. A very similar technique was tried in Russia in the 1960s, using rockets and artillery shells. Later, there were attempts to make rain fall by throwing sand into clouds from airplanes. All these attempts failed.

In 1946, Vincent Joseph Schaefer (1906–93) and Bernard Vonnegut (1914–97)—*see* APPENDIX I: BIOGRAPHICAL ENTRIES—were working as assistants to the Nobel Prize–winning chemist Irving Langmuir (1881–1957) at the General Electric Research Laboratory in Schenectady, New York. The team was studying the problem of icing on the wings of aircraft (*see* FLYING CONDITIONS), and they needed to know how icing is caused. Schaefer used a refrigerated box. The temperature inside the box was held at a constant -9.4°F (-23°C), and Schaefer added different kinds of particles to see what would cause ice crystals to form. There was a spell of very hot weather in July of that year, and Schaefer found it difficult to keep the box cold enough for his purpose. To chill the air inside the box, on July 13 he dropped some crushed dry ice (solid carbon dioxide), at -109°F (-78°C) into the box. Ice crystals formed the instant the dry ice entered the box, and there was a miniature snowstorm. Shortly after that, Bernard Vonnegut found that ice crystals formed when he burned SILVER IODIDE, allowing the smoke to enter the box. Further investigation revealed that dry ice was sharply lowering the temperature and causing ice crystals to form by homogenous nucleation and silver iodide crystals triggered heterogeneous nucleation (*see* FREEZING NUCLEI).

On November 13, 1946, Schaefer dropped 6 pounds (2.7 kg) of dry ice pellets from an airplane into a cloud over Pittsfield, Massachusetts. This started a snowstorm. Further experiments followed and by the 1950s commercial companies were offering cloud-seeding services. Silver iodide was much more convenient to use than dry ice, although dry ice is still used. Salt crystals are also used.

Silver iodide or dry ice are the most effective seeding agents where temperature inside the cloud is 5–23°F (between -15°C and -5°C). Salt crystals that are larger than most cloud droplets (more than about 10 μm across) make bigger liquid droplets form. The bigger droplets, 30 percent to 60 percent larger than those that were present previously, are heavier and consequently rain can be induced to fall from a cloud composed of droplets that are too small to fall.

Other particles are also used. These include grains of volcanic dust and clays (such as kaolinite, which initiates ice-crystal formation at 15.8°F, -9°C), some proteins, and bacteria (such as *Pseudomonas syringae,* which initiates ice-crystal formation at 28.4°F, -2°C). Others work best at temperatures between 5°F (-15°C) and 10°F (-12°C), but none of them are as effective or as simple to disperse as silver iodide.

Dry ice is administered by being dropped from an aircraft flying above the cloud. It is most effective when it is in the form of pellets about the size of peas. These produce a curtain of tiny ice crystals as they fall through the cloud. Silver iodide is released from aircraft or from the ground beneath the target cloud.

The addition of freezing nuclei can also reduce the size of hailstones or even prevent hail formation entirely. An airplane flying at the base of a cumulonimbus storm cloud (*see* CLOUD TYPES) releases particles into the updrafts. Increasing the number of freezing nuclei causes more small ice crystals to form. Freezing the supercooled water droplets onto a much larger number of much smaller crystals prevents the formation of big hailstones and may produce hailstones that are small enough to melt completely before reaching the ground.

It is possible to inject an excessive amount of nucleating material into the cloud. This is called overseeding. The aim of cloud seeding is to produce ice crystals that will grow by the Bergeron–Findeisen mechanism until they are large enough to fall as precipitation. If the cloud is overseeded, however, a much larger number of ice crystals will form, but they will be too small to fall and there will be so many of them that the cloud is depleted of supercooled droplets. This is a condition in which ice crystals cannot grow, because their growth requires supercooled liquid droplets as a source of moisture. The result is that while seeding may increase precipitation, overseeding inhibits it.

For a long time it was impossible to tell whether cloud seeding really worked. PRECIPITATION that fell from a cloud might have fallen in any case. The evidence now is that seeding can increase the amount of rain or snow that falls by at least 5 percent and sometimes by much more, but doubts remain, and in Kansas some farmers oppose hail-suppression programs, believing these reduce rainfall.

There are weather modification programs based on cloud seeding in several states, including Kansas, Colorado, Texas, Oklahoma, and North Dakota.

Further Reading

Cotton, William R. "Weather Modification by Cloud Seeding: A Status Report 1989–1997." Department of Atmospheric Sciences, Colorado State University. Available online. URL: http://rams.atmos.colostate.edu/gkss.html. Accessed February 14, 2006.

Hinds, Stacey. "Cloud Seeding." Denver Water Community Relations. Available online. URL: www.denverwater.org/cloud_seeding.html. Accessed February 14, 2006.

cloud types Clouds vary widely in appearance. Their shape is one of the factors used in classifying them (*see* CLOUD CLASSIFICATION) into genera, species, and varieties. Additional names refer to accessory clouds, and there are also many popular names for clouds. The names of clouds are arranged here alphabetically.

Abraham's tree is a popular name for cirrus radiatus, when this cloud consists of long, parallel bands that seem to radiate from a particular point on the horizon.

Actiniform is an adjective that describes a cloud pattern in which lines of clouds radiate from a central point or branch from one another like the branches of a tree. Actiniform clouds form by CONVECTION and the pattern covers an area about 90–150 miles (145–240 km) in diameter. Clouds of this type commonly occur in groups over areas in which subsiding air, chilled from below by cold ocean currents, produces INVERSIONS. Actiniform clouds were recognized only when satellite images became available. These provided views over an area wide enough for the pattern to be seen.

Altocumulus (Ac) is a genus of middle clouds, which are composed of water droplets. Altocumulus is white, gray, or both white and gray, and is made up of elements, each about 1° to 5° across, which is approximately the thickness of three fingers held at arm's length. Sometimes there is shading around the elements, sometimes not. The elements are arranged in lines or waves and made so close together that their edges merge and they form a sheet of cloud. There are often irisations (*see* OPTICAL PHENOMENA) around the edges of the elements.

Altocumulus cloud is very variable in appearance. Small vertical air movements produce the wavy bands. ***(Ralph F. Kresge, Historic NWS Collection)***

Altocumulus is difficult to describe, because its appearance is extremely variable. In summer, it often forms late in the evening, lasts through the night, but disappears during the course of the following morning. At night, the lower part of the cloud absorbs heat radiated from the ground surface, but loses heat by radiation from the upper surface. This produces a precarious balance between water droplets that are cooled at the top of the cloud and sink, and water droplets that are warmed at the base of the cloud and rise. The following morning the cloud continues to absorb radiation from below, but also absorbs more direct sunlight from above than it radiates away and the entire cloud warms, evaporating its water droplets. Altocumulus often has a wavy or banded appearance because of small vertical movements of this kind within it.

Altocumulus has little predictive value. Its variability is evident from the large number of species and varieties of it that can be seen. It occurs in the species castellanus, floccus, lenticularis, and stratiformis, and in the varieties duplicatus, lacunosus, opacus, perlucidus, radiatus, translucidus, and undulatus.

Altostratus (As) is a genus of middle clouds, which are composed of water droplets. Altostratus appears as a fibrous or striated veil, or a uniform sheet of cloud, and is grayish or bluish in color. It does not cause haloes (*see* OPTICAL PHENOMENA). The Sun or Moon can sometimes be seen through it as though through ground glass, but it can also be thick enough to obscure them totally. It is similar to cirrostratus, with which it often merges imperceptibly, but it forms at a lower level.

Altostratus develops at warm FRONTS, where warm, moist air rises over cooler air. Its appearance is usually an indication of approaching precipitation. A sky that is overcast with altostratus is often described as "watery."

There are no species of altostratus, but it occurs in the varieties duplicatus, opacus, radiatus, translucidus, and undulatus.

Cloud such as nimbostratus, that forms a flat, featureless sheet covering most or all of the sky is described as amorphous cloud.

An arch cloud is a stationary wave cloud, usually altostratus, which extends for a considerable distance along a mountain range with a wind blowing beneath it. The cloud is shaped like an arch and the wind blows down the mountainside as a FÖHN WIND. When seen from a distance, the arch indicates the approach of the wind. The Chinook Arch indicates the approach of a chinook wind (*see* LOCAL WINDS) in the Rocky Mountains of North America and the Southern Arch indicates the approach of a similar wind in the Southern Alps of New Zealand.

A thin veil of altostratus cloud over Pompano Beach, Florida, in October 1980. Altostratus usually heralds rain or snow. ***(Ralph F. Kresge, Historic NWS Collection)***

Arcus is a supplementary feature of cumulonimbus clouds in which the lower, darkest part of the cloud is arched. This feature occurs most commonly in clouds that form along SQUALL lines. *Arcus* is a Latin word that means "bow" or "curve."

A banner cloud is a wave cloud that extends downwind from a mountain peak, like a flag flying from the summit.

Banner cloud extending downwind from a mountain peak in southwestern Alaska, photographed in April 1980. ***(Captain Budd Christman, NOAA Corps)***

Billow clouds are a type of undulatus that consist of parallel rolls of cloud forming cloud bars (*see* CLOUD) separated by clear sky. Billow clouds are produced in conditions of high relative HUMIDITY by the TURBULENT FLOW of air associated with CLEAR AIR TURBULENCE. The turbulence produces SHEAR waves and EDDIES and the billow clouds mark the crests of the waves, where air has risen far enough for its water vapor to condense. Each billow cloud lasts for only a short time before it is dissipated by the turbulence.

Calvus (cal) is a species of cumulonimbus cloud that lacks or is in the process of losing the billowing, cauliflower-like structures and cirriform appendages from its upper part. *Calvus* is the Latin word for "bald."

A cap cloud is a flat-topped, cumuliform cloud that is seen blanketing a mountain peak. It is an orographic cloud that is also associated with a föhn wind. The wind extends the cloud for some distance down the LEE side of the mountain, producing a föhn wall.

Capillatus (cap) is a species of cumulonimbus cloud in which the uppermost part has a fibrous or striated, cirriform structure. The name of the species is derived from the Latin *capillus,* which means "hair."

Castellanus (cas) is a species of clouds that have many vertical protuberances looking like small clouds arising from the main cloud. These are often shaped like the turrets of a castle and are most often seen on altocumulus, but also occur on clouds of the genera cirrus, cirrocumulus, and stratocumulus. *Castellanus* is the Latin word for "castle."

Cirr- (or cirro- or cirri-) is a prefix derived from the Latin word *cirrus,* which means a curl, such as a curl of hair. It is attached to cloud genera that consist of wispy, fibrous cloud elements.

Cirriform describes a cloud that is stretched into long, fine, curling filaments that resemble the cloud genus cirrus.

Cirrocumulus (Cc) is a genus of high clouds, which are composed entirely of ICE CRYSTALS. Cirrocumulus appears as small, white patches or sheets, or as more or less spherical masses, called elements, with no shading around or between them. Each of these elements has an apparent width of about 1°, which is approximately the width of a little finger held at arm's length. The elements are arranged in more or less regular patterns resembling the ripples seen in sand on the seashore, or, less commonly, form groups or lines. Cirrocumulus is usually a degraded form of cirrus or cirrostratus, from which it retains a fibrous appearance. Cirrocumulus should not be confused with small altocumulus that is sometimes seen at the edge of sheets of altocumulus.

Cirrocumulus clouds are composed entirely of ice crystals. These were photographed at Grand Rapids, Michigan, in November 1979. ***(Ralph F. Kresge, Historic NWS Collection)***

Cirrocumulus occurs as the species castellanus, floccus, lenticularis, and stratiformis, and as the varieties lacunosus and undulatus. A mackerel sky is produced by cirrocumulus.

Cirrostratus (Cs) is a genus of high clouds, which are composed entirely of ice crystals. Cirrostratus appears as a thin, white veil that does not blur the outlines of the Sun or Moon, although it often gives rise to haloes. Sometimes it is so thin it does no more than give the sky a pale, milky appearance. At other times, it has a distinctly fibrous appearance, as though it consists of tangled filaments.

Cirrostratus often forms on a warm front and if cirrus appears first, then thickens until it becomes cirrostratus, it is likely that an active DEPRESSION is approaching. This may become stationary and fill, or may change direction, but if it continues its approach it will probably bring precipitation.

The species of cirrostratus are fibratus and nebulosus, and it occurs in the varieties duplicatus and undulatus. The supplementary feature virga is sometimes seen below the base.

Cirrus (Ci) is a genus of high clouds, which are composed entirely of ice crystals. Cirrus appears as long, wispy filaments, narrow bands, or white patches, always with a fibrous appearance. Cirrus is often seen

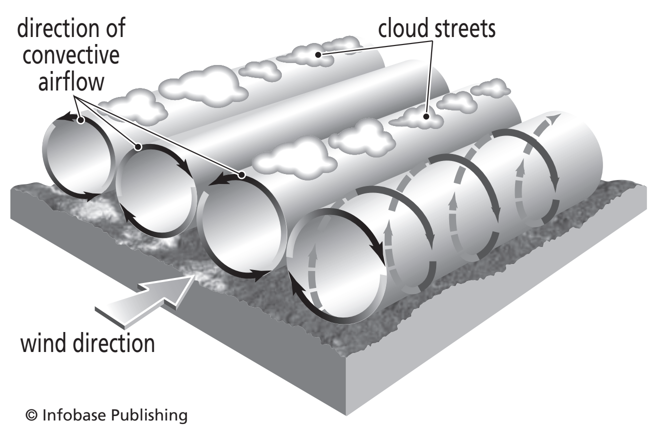
Cirrostratus forming a thin veil through which the Sun appears as a halo. ***(Ralph F. Kresge, Historic NWS Collection)***

Long, wispy fingers of cirrus clouds known as mares' tails, photographed over the Coast Range, Purisima Creek Redwoods, Bay Area, California, in October 2003. Fog is beginning to roll in over the mountains. ***(Albert E. Theberge, NOAA Corps)***

ahead of an approaching warm front. It occurs as the species castellanus, fibratus, floccus, spissatus, and uncinus, and the varieties duplicatus, intortus, radiatus, and vertebratus.

A cloud street is a row of small fair weather cumulus clouds that are aligned with the wind direction. Cloud streets most often form in the early morning and evening and they require a wind speed of more than about 13 MPH (6 m/s).

As the wind flows across the warm ground, small irregularities in the surface can trigger the development of thermals (*see* CONVECTION) that are carried downwind. The thermals form a series of convection cells, but in the early morning and evening, when the ground surface is cooler and convection is less vigorous, a



Cloud streets consist of small cumulus clouds in rows parallel to the wind direction. This pattern is due to the spiraling airflow produced by the combination of convection and wind.

A cloud street is a row of small fair weather cumulus clouds aligned with the wind direction. This cloud street was photographed on August 14, 1971. ***(C. True, NOAA/AOML/Hurricane Research Division)***

Cumulonimbus with a large "anvil" (incus). ***(Historic NWS Collection)***

breeze may cause the cells to merge into a series of convective spirals traveling downwind.

Air cools as it is carried upward in the spirals. If, at the top of each spiral, it cools to below its dew point temperature (*see* DEW), some of its water vapor will condense to form a cumuliform cloud. Before the cloud has time to grow, the air has descended on the downward side of the spiral and its temperature has risen to above its dew point. Consequently, small clouds form at the top of each turn in the spiral, to produce a line of clouds parallel to the wind direction.

A cold cloud is one in which the temperature is below freezing throughout and RAINDROPS form by the Bergeron–Findeisen mechanism.

Congestus (con) is a species of cumulus clouds, which are large and growing rapidly, usually by the development of towering, billowing structures in the upper parts of the cloud. A cumulus congestus (Cu_{con}) cloud looks like a cauliflower. The name of the species is derived from the Latin verb *congere,* which means "to bring together."

Contessa del vento is a type of lenticular cloud in which the base is rounded and the upper surface bulges. Sometimes several clouds of this type form one above the other, in a stack. The name is from the cloud that develops in a westerly airstream near Mount Etna.

Convective cloud develops vertically as a result of convection. Cumuliform clouds are of this type.

A crest cloud (cloud crest) is a cloud that marks the crest of a lee wave (*see* LEE). The cloud is seen above or slightly on the lee side of a mountain peak or the top of a high hill and it remains stationary in relation to the land below.

Cumuliform is an adjective used to describe the shape of a cloud that resembles a cloud belonging to the cloud genera cumulus and cumulonimbus. A cumuliform cloud has a fleecy appearance, like cotton wool, or is heaped up with many protuberances, like a cauliflower.

Cumulonimbus (Cb) is a genus of dense cloud with a low base that often extends vertically to a great height, sometimes all the way to the tropopause (*see* ATMOSPHERIC STRUCTURE). It forms mountainous and towering shapes, but the uppermost part is usually smooth and the top flattened, marking the level beyond which air is unable to rise by convection. It may form the accessory cloud incus.

Cumulonimbus to the rear of a squall, as portrayed in *Wolken im Luftmeer* (Clouds in the Ocean of the Atmosphere), a cloud atlas produced by aircrews in 1917 for the German Air Forces. ***(Historic NWS Collection)***

These small, fleecy, cumulus clouds form in fine weather and are too small to produce any precipitation. They are called fair weather cumulus. These clouds were photographed in December 1977 over Coconut Creek, Florida. ***(Ralph F. Kresge, Historic NWS Collection)***

A cumulus cloud that is growing rapidly. It is called cumulus congestus and this one is over Limon, Colorado. ***(Cruse/Crowley, Historic NWS Collection)***

Cumulonimbus cloud brings precipitation, which is often heavy, and it is the cloud associated with THUNDERSTORMS, TROPICAL CYCLONES, and TORNADOES. The great depth of cloud in which light is scattered by water droplets makes the lower part of a cumulonimbus cloud very dark and often menacing.

Cumulonimbus is classified as a low cloud because of the height of its base (*see* CLOUD BASE). It occurs as the species calvus and capillatus, and sometimes with the accessory cloud, virga.

Cumulus (Cu) is a genus of clouds that develop vertically as warm air rises by convection. As it rises the air cools adiabatically (*see* ADIABAT) and some of its water vapor condenses into droplets, forming the cloud, which is of a fleecy, or billowing shape, sometimes called "cotton wool" cloud. Cumulus clouds are isolated from one another. Blue sky is often visible between them, so their boundaries are sharply defined. Small, scattered cumulus clouds seen on a fine day are known as fair weather cumulus. At other times cumulus may be immersed in clouds of other types, so it is more difficult to distinguish. The base of a large cumulus cloud is dark, because of the density of water droplets by which light is scattered on its way to the ground. The sunlit upper parts of the cloud are very bright.

Cumulus is classified as low cloud, by the height of its base although its upper parts may extend to middle altitudes. The cumulus species are congestus, fractus, humilis, and mediocris, and it also occurs as the variety radiatus.

Duplicatus is a variety of clouds, which comprise layers, sheets, or patches of clouds that are at different heights but that merge or overlap each other as seen from the ground. Duplicatus is seen in association with the cloud genera cirrus, cirrostratus, altocumulus, altostratus, and stratocumulus. *Duplicatus* is a Latin word that means "duplicated."

Fair weather cumulus comprises small, white, fleecy clouds that appear in fine weather and that deliver no precipitation. Their scientific name is cumulus humilis. The clouds are all at the same height and have a somewhat flattened appearance. This is due to the presence of a temperature INVERSION immediately above them. The CLOUD BASE is determined by the condensation level, but there is warmer air above the clouds. CLOUD DROPLETS that rise by convection enter air in which they immediately evaporate.

A fallstreak hole is a hole that sometimes develops in clouds composed of supercooled water droplets (*see* HUMIDITY). Droplets in part of the cloud freeze and then grow into raindrops by the Bergeron–Findeisen mechanism. The raindrops fall from the cloud, often in the form of virga, or fallstreaks, leaving behind clear air from which the cloud droplets have been removed.

False cirrus is cloud that resembles cirrus, but that is formed from the upper part of a cumulonimbus cloud that has dissipated or from which it has become detached.

Fibratus (fib) is a species of clouds, which consist of long filaments that are almost straight or irregularly curved and that do not end in hooks. Fibratus may occur as a detached cloud or form a thin veil across part of the sky. The species is most often seen in clouds of the genera cirrus and cirrostratus. The name of the species is derived from the Latin word *fibra,* which means "fiber."

A fibril is a trail of cloud that is sometimes seen extending from a cumulonimbus cloud. It consists of droplets the size of drizzle droplets (*see* PRECIPITATION). These are large enough to have a TERMINAL VELOCITY that exceeds the force of the air currents within the cloud, so they are able to escape from it.

Floccus (flo) is a species of clouds, which consist of elements, each of which has a cumuliform appearance. The base is ragged to a greater or lesser extent. Floccus often occurs with virga. The species is most often seen with the cloud genera cirrus, cirrocumulus, and altocumulus. *Floccus* is a Latin word meaning a tuft of filaments or woolly hairs.

Föhn cloud is a cloud, usually of the lenticularis type, that forms on the lee side of a mountain range. Such clouds are often associated with a FÖHN WIND. Föhn clouds are produced by lee waves in air that has crossed the mountains, while air flowing down the lee side of the mountains produces the föhn wind.

A föhn wall is the upper surface of the cap cloud blanketing a mountain peak, as seen from the lee side of the mountain. The cloud extends for some distance down the mountainside, carried by the airflow that produces the föhn wind, and its upper side appears as a solid wall of cloud.

Fractocumulus is fragments of broken or ragged cloud that have been torn from cumulus or that are the remains of cumulus that has dissipated. Fractocumulus is the cloud species cumulus fractus (Cu_{fra}).

Fractostratus is fractus belonging to the cloud species St_{fra}. It remains behind as the stratus dissipates.

Fractus (fra) is a species of clouds that are seen only with the cloud genera cumulus and stratus. Fractus consists of fragments of cloud that look as though they have been torn from the parent cloud, or are all that remains after the parent cloud has dispersed, and this is indeed how fractus is formed. *Fractus* is a Latin word that means "broken."

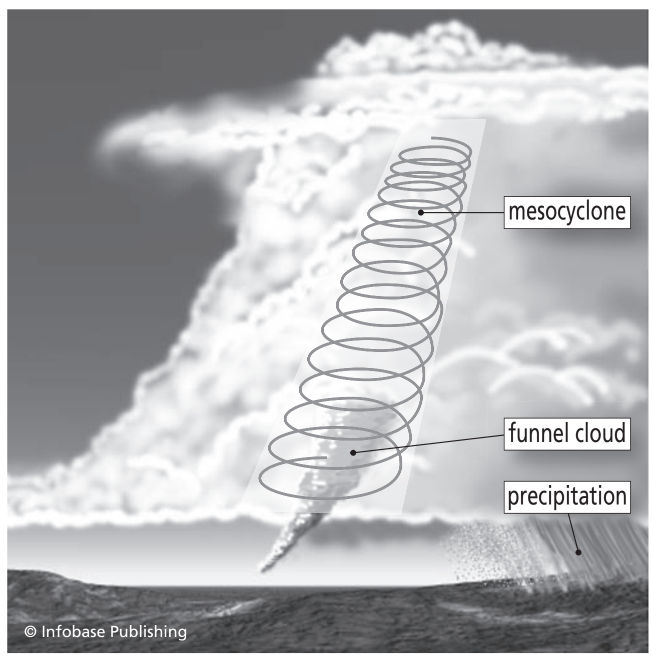
Fumulus is a cloud layer (*see* CLOUD BASE) that is so thin and tenuous as to be barely visible.

A funnel cloud is a cloud shaped like a funnel that develops inside a MESOCYCLONE and then descends through the base of a cumulonimbus cloud. It hangs from the parent cloud, usually snaking erratically, and if it touches the ground it becomes a TORNADO. Air in the funnel rotates, almost always cyclonically (counterclockwise in the Northern Hemisphere), but there are rare exceptions. Its energy is derived mainly from the LATENT HEAT of condensation, and so it needs a constant supply of moist air to sustain it. The cloud is visible because of the condensed water droplets it contains. A funnel cloud is gray in color, and although most funnel clouds are wider at the top than at the bottom, some are wider at the base. Their width and length vary greatly.

Genitus describes the emergence of a new cloud from a mother cloud, where only one part of the mother cloud is affected by the change.

A glaciated cloud is one in which all the particles are ice crystals.

High cloud is cloud that has a base at above 20,000 feet (6,000 m) altitude. Cirrus, cirrocumulus, and cirrostratus are classified as high clouds.



If the air begins to spin inside the cloud, near the center of a mesocyclone, the rotation may extend downward until it protrudes beneath the cloud base as a funnel cloud.

Humilis (hum) is a species of cumulus clouds that have flat bases and little vertical development. They represent cumulus that has failed to grow. *Humilis* is a Latin word that means "lowly."

Ice-crystal cloud is cloud that consists entirely of ice crystals because the whole of it is above the FREEZING LEVEL.

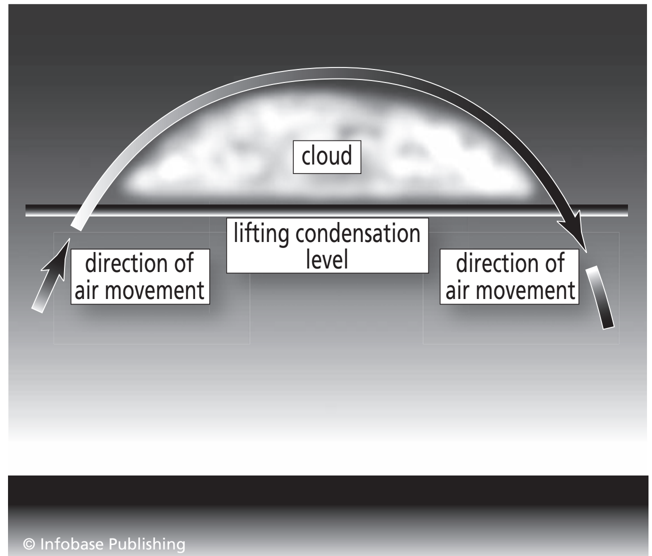
Incus (anvil) is a supplementary cloud feature that comprises the mass of cirriform cloud at the top of a cumulonimbus cloud. This is often swept by the wind into the shape of an anvil. *Incus* is the Latin word for "anvil," and "anvil" is what an incus is often called.

The incus is formed from ice crystals. As the high-level wind sweeps them away from the top of the parent cloud they begin to fall. Outside the cloud, the relative humidity of the air is below 100 percent, so ice crystals falling into it vaporize by SUBLIMATION. As the remaining crystals are carried farther, they also eventually reach air into which they vaporize. It is this process that produces the characteristic anvil shape.

Intortus is a variety of cirrus clouds in which the cloud consists of filaments that curve irregularly and appear to be entangled haphazardly. The name is derived from the Latin word *tortus,* which means "crooked."

Iridescent cloud is cloud that is partly brightly colored, most often with patches of red and green but sometimes with violet, blue, or yellow. The color is caused by the DIFFRACTION of sunlight or moonlight by small water droplets or ice crystals. For iridescence (also called irisation) to occur the particles must be of approximately uniform size and the cloud must be in the same part of the sky as the Sun or Moon. Iridescent clouds are most often seen when the Sun or Moon is behind cloud or some barrier; when it is in full view its light is so intense as to make the colors invisible. Which colors are seen depends on the size of the droplets or crystals and the angle between the Sun, cloud, and observer.

Lacunosus is a variety of clouds that appear as patches, layers, or sheets of cloud and that include approximately round holes distributed more or less evenly so the cloud and holes form a pattern reminiscent of a net. The cloud is usually thin and the holes often have fringes around the edges. Lacunosus occurs with the cloud genera cirrocumulus and altocumulus. The name lacunosus is derived from the Latin word *lacus,* which means "lake." This is the same source that gives us lacuna, meaning a hole or missing portion.



Lenticularis is a cloud shaped like a lens. It forms when air is moving up and down with a vertical wave motion, and the lifting condensation level lies below the wave crests.

A layer cloud is a stratiform cloud that resembles a sheet and is of limited vertical extent.

A lenticular cloud is a type of altocumulus lenticularis (Ac_{len}) that is often seen on the lee side of mountains. As stable air crossing the mountains is forced to rise and then descends to its former level, a wave motion becomes established. This produces a series of lens-shaped clouds extending downwind as far as the wave pattern. These are sometimes called wave clouds.

Lenticularis (len) is a species of clouds that are most commonly found in association with the cloud

Wave clouds over Mount Pisgah, North Carolina, photographed in January 1980. ***(Grant W. Goodge, Historic NWS Collection)***

A lenticular cloud (altocumulus lenticularis) resembling a flying saucer over the Rocky Mountains at Fort Collins, Colorado, on February 21, 1940. Lenticular clouds are associated with strong winds and standing waves. ***(Maxwell Parshall, Historic NWS Collection)***

Mammatus cloud over Tulsa, Oklahoma, June 2, 1973. ***(NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory [NSSL])***

genera cirrocumulus, altocumulus, and stratocumulus. The cloud has the shape of a lens, usually with well defined outlines, and sometimes has a very dramatic appearance. It can resemble a flying saucer!

Lenticularis forms when stable air (*see* STABILITY OF AIR) moves over an obstruction, such as a hill or coastline. This forces the air to rise, but, being stable, it then sinks to its former level. If the air is moist, it may be raised to its lifting condensation level (*see* CONDENSATION), above which its water vapor starts to condense into droplets. As it sinks, the air moves below its lifting condensation level once more and condensation ceases. The vertical movement, with condensation occurring only at the top of the wave, is what produces the lens shape. The name of the species is Latin and derived from *lenticula,* which means lentil or lens (from the similarity of shape).

Low cloud forms with a base below 6,500 feet (2,000 m) altitude. Stratus, stratocumulus, and nimbostratus are classified as low clouds. Cumulus and cumulonimbus are sometimes counted as low clouds, because although they extend vertically, sometimes to a great height, their bases are often below 6,500 feet (2,000 m).

A mackerel sky comprises cirrocumulus cloud in which the individual units of cloud are swept by the high-level wind into long, parallel rows, so they form an orderly pattern reminiscent of the pattern of scales on the back of a mackerel fish. It frequently forms ahead of a warm front along which the rising warm air is unstable. This indicates that the front is likely to bring showers, possibly heavy ones, with bright intervals between them. Traditionally, a mackerel sky has also been taken to indicate a strengthening of the wind.

Mammatus is a supplementary cloud feature that sometimes forms on the underside of a large incus. It appears as many smooth, udder-shaped protrusions from the cloud base. These form when ice crystals at the top of the incus sublimate (*see* SUBLIMATION) into the dry air above them. Sublimation absorbs latent heat, chilling local areas in the cloud. These become denser and sink through to the bottom of the anvil. Mammatus forms only in very large storm clouds, so it is an indication of severe storms, possibly generating tornadoes.

Mares' tails are made from cirrus fibratus cloud that appears as long, wispy strands that curl at the ends. Cirrus clouds extend vertically for only a short distance. Their appearance is wispy partly because they are too thin to obscure the sky above them fully and partly because the ice crystals of which they are composed are carried by the wind. This is what sweeps them into long streamers. Where the wind weakens, crystals start to fall. Then they enter drier air and vaporize. This produces the curls at the ends of the tails.

The longer the filaments of the tails, the stronger is the wind producing them. Although this high-level wind is stronger than the surface wind beneath the clouds, and often blows from a different direction, cirrus frequently forms near the top of an approaching warm front and the high-level wind that shapes it is blowing behind the front. If the high-level wind is strong, the surface wind behind the front is also strong, and so the appearance of mares' tails is often a sign that the wind will strengthen within the next few hours. Sailors recognized this long ago, and the link is recorded in the saying:

Mackerel sky and mares' tails
Make lofty ships carry low sails.

Mediocris (med) is a species of cumulus clouds that have fairly small protuberances and are of moderate vertical extent. The name of the species is a Latin word that means "of middle height."

Middle cloud is cloud that forms with a base between 6,500 feet and 20,000 feet (2,000–6,000 m) altitude. Altocumulus and altostratus are classified as middle clouds.

Mixed cloud is cloud that contains both water droplets and ice crystals. The cloud base is below the freezing level, but the cloud also extends above it.

Mother cloud is a cloud from which other clouds have been produced and that is seen at the same time as the clouds to which it gave rise.

Mutatus is a cloud development in which the shape of the cloud is changing fairly rapidly because of new cloud masses that are growing from it.

Nacreous cloud, also called mother-of-pearl cloud, comprises bright clouds, white usually tinged with pink, that are occasionally seen in high latitudes when the Sun is just below the horizon (shortly before dawn or after sunset). It resembles the mother-of-pearl that lines the inside of some seashells. Nacreous clouds form in winter in the lower to middle stratosphere (*see* ATMOSPHERIC STRUCTURE), at heights of about 12–19 miles (20–30 km) above sea level, in air at a temperature of about –112°F (–80°C). They are composed of ice crystals and develop on the crests of waves generated by the low-level movement of air across mountains. Polar stratospheric clouds are a variety of nacreous cloud.

Nebulosus (neb) is a species of clouds that form a layer or veil with no clearly distinguishable features. The species occurs with the cloud genera cirrostratus and stratus. The name of the species is the Latin word that means "mist."

Nimbostratus (Ns) is a genus of low, gray, fairly uniform clouds that often deliver steady, continuous rain or snow. Although its base is low, nimbostratus usually extends vertically to above 6,500 feet (2 km), and it is thick enough to obscure the Sun and Moon completely, making daylight dull and nights exceedingly dark. The cloud is shapeless, dark, and sometimes appears to be faintly illuminated from the inside. This is due to breaks in the nimbostratus that reveal paler stratus above it. Nimbostratus often forms scud.

Like stratus, which it closely resembles, nimbostratus forms when moist, stable air is forced to rise and its water vapor condenses. Consequently, it occurs on warm fronts and also on mountains due to orographic lifting. There are no species or varieties of nimbostratus.

Nimbus is the Latin word for "cloud," which originally meant a bright cloud or the halo or aureole surrounding the head of a holy person. In his 1803 classification of clouds, Luke Howard used the word to imply "rain" (the Latin for rain is *pluvia*). Nimbus is now used in the form nimbo- as a prefix attached to the cloud genus stratus, to give nimbostratus, and as a suffix to the genus cumulus to give cumulonimbus. In both cases the term associates the generic names with the idea of precipitation.

Noctilucent cloud is occasionally seen on summer nights in high latitudes. It shines with light reflected from the Sun, which is well below the horizon. The cloud forms in the upper mesophere (*see* ATMOSPHERIC STRUCTURE), at a height of about 50 miles (80 km). How it forms is uncertain, but it may be by the DEPO-

Nimbostratus cloud often delivers steady, continuous rain or snow. ***(Ralph F. Kresge, Historic NWS Collection)***

Noctilucent cloud shines at night with reflected sunlight, although the Sun is below the horizon. ***(Pekka Parviainen, Polar Image)***

SITION of traces of water vapor onto particles swept in from space.

Opacus is a variety of clouds in which the cloud forms a layer, sheet, or patch that is dense enough to hide the Sun or Moon completely. Opacus occurs with the cloud genera altocumulus, altostratus, stratocumulus, and stratus. *Opacus* is the Latin word that means "opaque."

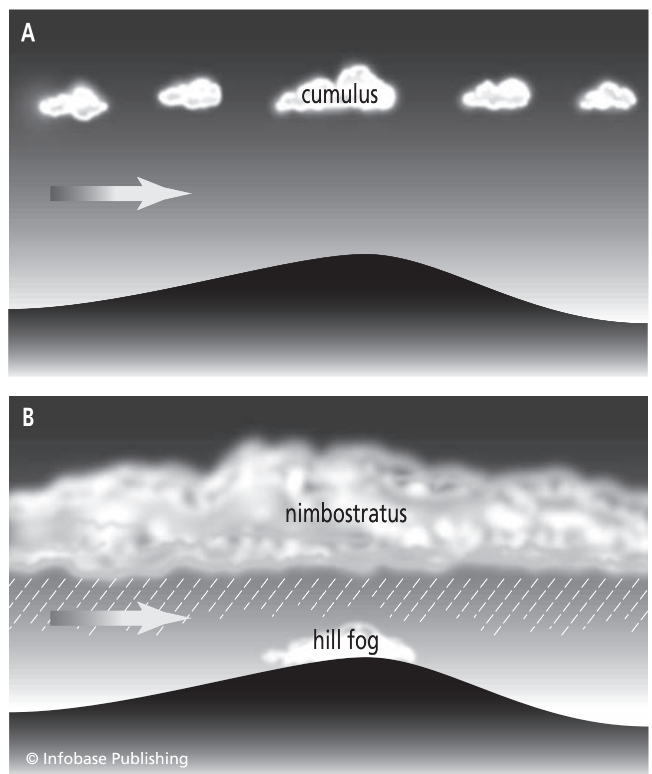
Orographic cloud is cloud that forms above high ground as a result of orographic lifting. As air is forced to rise, its flow becomes somewhat turbulent (*see* TURBULENT FLOW). This mixes the air, so its temperature and humidity are the same throughout the affected layer. If the air is fairly buoyant (*see* BUOYANCY), small cumulus clouds will form, their positions indicating the degree of lifting in different places. Because of the mixing, their bases will all be at the same height. On the windward side (*see* WIND) of the high ground there will be a few small clouds. The largest cloud will form above the crest of the hill, and downwind the clouds will be smaller, but larger than those on the windward side. If the air is moist, it will form a thicker layer of nimbostratus lying above the hill crest and extending to both sides, with a cap of stratus sitting as hill FOG on the highest ground. Lenticular cloud is also a form of orographic cloud.

Pannus is an accessory cloud that comprises ragged patches of cloud attached to or beneath another cloud. The word *pannus* is Latin for "shred." Pannus is most often seen with cumulonimbus, cumulus, altostratus, and nimbostratus.

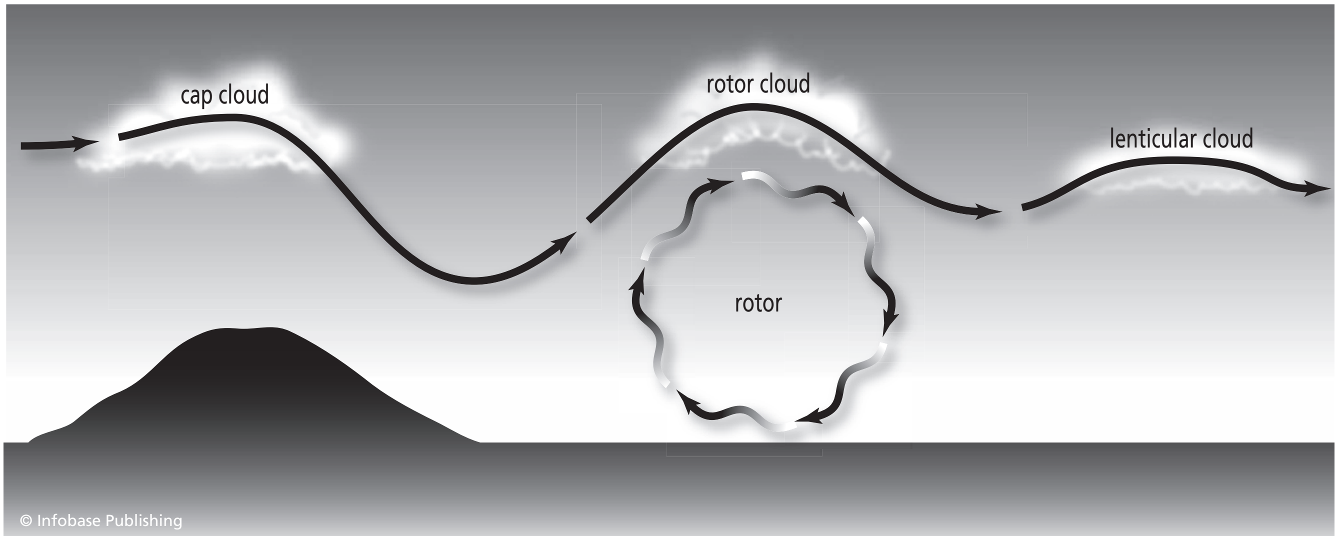
Perlucidus is a variety of clouds in which the cloud forms an extensive layer, sheet, or patch that includes open spaces. These may be very small, but are quite distinct. Blue sky can be seen through them, and when they are in the correct position the Sun or Moon can shine through them. Perlucidus occurs with the cloud genera altocumulus and stratocumulus. The name *perlucidus* is derived from the Latin words *per,* which means "through," and *lucidus,* which means "bright" (from the verb *lucēre,* "to shine").

Pileus is an accessory cloud that extends horizontally for only a short distance, but forms a smooth, thin covering above or attached to the top of a cumuliform cloud, like a cap or hood. It is most often seen while the main cloud is developing. *Pileus* is the Latin name for a felt cap.

Polar mesospheric cloud is a name for noctilucent cloud that is preferred scientifically because it is more descriptive. Rather than suggesting a cloud that is visible at night, the preferred name indicates that it is seen only in polar latitudes and that it occurs in the upper mesosphere.



Orographic cloud forms as air approaches high ground (from the left in this drawing) and is forced to rise. The cloud forms above the summit and to the upwind and downwind sides of the summit. The type of cloud depends on the relative humidity and buoyancy of the air.



A rotor cloud is a small cumulus cloud that forms downwind of a steep-sided hill, at the crest of the wave induced in the flow of air by its passage over the hill.

Praecipitatio is a supplementary feature of clouds that consists of PRECIPITATION falling from the cloud and appearing to reach the ground. The name is the Latin for "I fall headlong." Praecipitatio is most often seen with cumulus, cumulonimbus, stratocumulus, nimbostratus, stratus, and altostratus clouds.

Radiatus is a variety of clouds in which the clouds are arranged as broad, parallel bands that, due to perspective, appear to converge at a point on the horizon or at two points at opposite sides of the horizon. The points of convergence are called radiation points. Radiatus occurs with the cloud genera cirrus, altocumulus, altostratus, stratocumulus, and cumulus. The name *radiatus* is derived from the Latin word *radiare,* which means "spoke," or "ray."

A rain cloud is any cloud from which rain or drizzle is likely to fall. The term has no precise meteorological meaning, but usually refers to nimbostratus. Altostratus, stratus, and cumulonimbus also produce rain, however, and so these may also be called rain clouds.

A rotor cloud is a cloud that forms at the crest of the first of a series of lee waves if the downwind side of the mountain is very steep. It is the forced movement of stable air (*see* STABILITY OF AIR) across a mountain that triggers the development of lee waves. A cap cloud often forms at the mountain peak, where water vapor condenses in the air that has been cooled adiabatically. Lenticular clouds may form farther downwind. On the lee side of a steep slope, the smooth flow of air associated with the lee waves breaks down and beneath the crest of the first wave the air may be rotating. This is called a rotor. Air within it is extremely turbulent, and occasionally a rotor may cause the wind direction at ground level to be the reverse of that in the waves themselves. A rotor can be very dangerous for aircraft.

A rotor cloud will develop at the top of the rotor if air is sufficiently humid for its water vapor to condense. The air within the cloud retains the turbulent motion of the rotor, producing a cloud that is much more cumuliform in shape than either the cap or lenticular clouds.

Scud is fragments of tattered cloud, most commonly of nimbostratus, which lie below the general CLOUD BASE.

A shelf cloud is a layer of cloud that projects like a shelf beneath the incus of a big cumulonimbus storm cloud. As the storm approaches, it is the incus that arrives first, as a thin layer of high-level cloud. This quickly thickens and its base becomes lower. Then a second layer of cloud appears below the anvil. This is the shelf cloud. It marks the region of the storm where warm air is being drawn into the cloud and its water vapor is condensing as it rises and grows cooler. The GUST front, caused by the inrush of air, is situated beneath the shelf cloud. Heavy PRECIPITATION usually commences near to where the shelf cloud is attached to the main cloud.

A snow cloud is a cloud from which snow falls or appears likely to fall. It differs from a rain cloud only in being colder. Nimbostratus may give continuous snow and cumulonimbus may produce snow showers, which may be heavy. ICE PRISMS and snow grains may fall from stratus. Significant amounts of SNOWFLAKES will form if the temperature high in the cloud is below -4°F (-20°C) and it is above 14°F (-10°C) in the lower part of the cloud. Snowflakes will melt before reaching the ground unless the air temperature between the CLOUD BASE and the surface is below about 39°F (4°C).

Spissatus (spi) is a species of the cloud genus cirrus that is sufficiently dense to appear grayish when viewed looking toward the Sun.

Squall cloud is a roll of dark cloud, often with mammatus, that forms along the leading edge of a SQUALL line. It is produced by eddies between the up- and down-currents.

A standing cloud is a cloud that remains stationary, usually above or close to a mountain peak or other high ground.

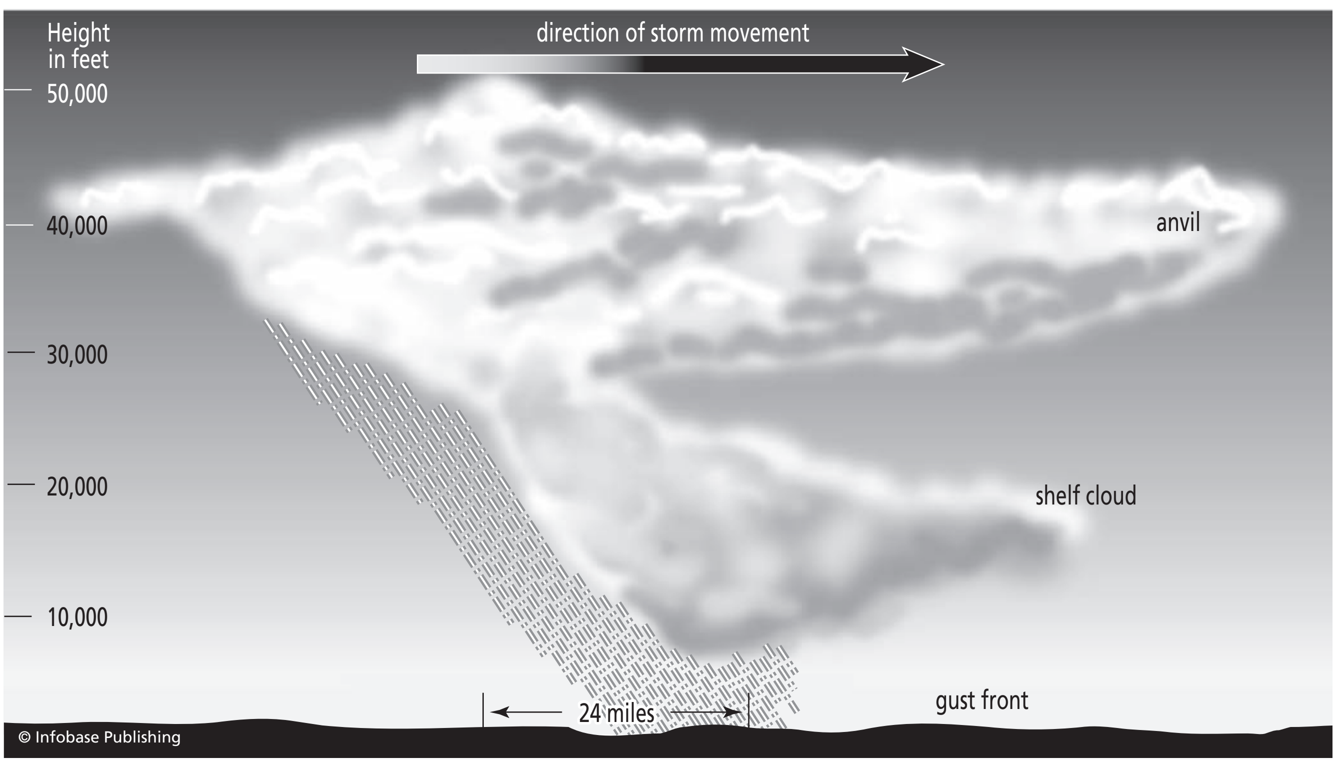
Strat- is a prefix that is derived from the Latin *stratum,* which is the neuter past participle of the verb *sternere,* which means "to strew." It is attached to cloud genera, species, and varieties that form extensive, horizontal sheets or layers, as though they were spread (or strewn) across the sky.

Stratiform is an adjective applied to clouds that form extensive horizontal layers.

Stratiformis (str) is a species of cumuliform clouds that spread across the sky to form an extensive sheet. The species occurs with the cloud genera cirrocumulus, altocumulus, and stratocumulus.

Stratocumulus (Sc) is a genus of low clouds that are composed of water droplets. It is seen as patches, sheets, or layer of gray, white, or both gray and white cloud. There are always dark areas, shaped as rolls or rounded masses. These sometimes merge into larger masses. They are not fibrous. The smallest elements have an apparent width of about 5°. The cloud is similar to altocumulus, but heavier and it occurs at a lower level.

Stratocumulus often has gaps that are large enough to allow sunlight to penetrate intermittently. When sunlight shines through gaps in the cloud at around



A shelf cloud is a layer of cloud, resembling a shelf, that projects from the main part of a large storm cloud.

Stratocumulus cloud, showing the typical dark rolls, over Coconut Creek, Florida, in November 1979. ***(Ralph F. Kresge, Historic NWS Collection)***

dawn or sunset its converging beams often illuminate dust and other solid particles in the air below the cloud forming crepuscular rays (*see* OPTICAL PHENOMENA). These are often described as the "Sun drawing water" and regarded as a warning of approaching rain, but stratocumulus does not indicate bad weather.

Stratocumulus develops where rising air encounters a ceiling of warmer air and is flattened against it. In winter it can produce an overcast sky lasting for several days. In summer, there is usually sufficient warmth for much of the cloud to evaporate, changing it into fair weather cumulus.

Stratocumulus occurs in the species castellanus, lenticularis, and stratiformis, and in the varieties duplicatus, lacunosus, opacus, perlucidus, radiatus, translucidus, and undulatus.

Stratus (St) is a genus of low clouds that form a uniform, gray layer. When stratus forms at the surface it is FOG, and as a cloud it resembles fog that is above the ground. It sometimes delivers drizzle, snow grains, or ice prisms, but if it is thin enough for the Sun or Moon to be discernible through it their outlines can be seen clearly. Stratus differs from altostratus only in the height of its base.

Stratus often forms in valleys and as hill fog, but also on warm fronts. When cirrostratus and altostratus are followed by the appearance of stratus, precipitation is very likely. In fine weather, however, stratus often forms overnight, especially over water, and "burns off" as the daytime temperature rises and the cloud droplets evaporate.

Stratus can occur as the species fractus and nebulosus, and in the varieties opacus, translucidus, and undulatus.

Streak cloud is an elongated fragment of fibrous cloud, commonly cirrus, that indicates the direction and strength of the WIND SHEAR.

A thunderhead is a cumulonimbus cloud that extends vertically to the tropopause, where it spreads downwind to produce an anvil-shaped incus of cirriform cloud. The incus is the "head" of a cloud that is likely to produce a THUNDERSTORM.

Trade cumulus, also called trade-wind cumulus, is cumulus cloud that forms over the ocean in the Tropics. It develops in air that is trapped beneath the trade wind INVERSION. This limits its vertical extent, producing clouds with flat tops at the height of the inversion and all of much the same size and shape.

Translucidus is a variety of clouds that cover a large proportion of the sky but through which it is possible to discern the position of the Sun or Moon, so the cloud is translucent. The variety most often occurs with the cloud genera altocumulus, altostratus, stratocumulus, and stratus. The name of the variety is derived from the Latin verb *translucere,* which means "to shine" (*lucere*) "through" (*trans*).

Tuba is a supplementary feature of clouds of the types that may give rise to TORNADOES or WATERSPOUTS. It consists of a tapering, funnel-shaped projection beneath the cloud base. *Tuba* is the Latin word that means "trumpet."

Uncinus (unc) is a species of cirrus clouds in which the cloud consists of long filaments that end in hooks,

Stratus cloud, forming a uniform, gray, featureless sheet. ***(Ralph F. Kresge, Historic NWS Collection)***

in the shape of commas, or in tufts, but not with a protruding upper part. Uncinus forms when the cloud is being swept out by strong winds in the upper troposphere. *Uncinus* is a Latin word that means "hook."

Undulatus is a variety of clouds in which sheets, layers, or patches of cloud undulate like waves. It is most often seen with the cloud genera cirrocumulus, cirrostratus, altocumulus, altostratus, stratocumulus, and stratus. The name of the variety is derived from the Latin *unda,* which means "wave."

A veil of cloud is a layer of cloud that is very thin. Objects can be seen through it.

Velum is an accessory feature of clouds that consists of a layer of cloud extending horizontally for a considerable distance above other clouds and sometimes connecting the tops of cumulus clouds. *Velum* is a Latin word that means "curtain," "veil," or "covering."

Vertebratus is a variety of cirrus clouds in which the cloud elements are arranged in a pattern reminiscent of the skeleton of a fish, with the long ribs clearly displayed. *Vertebratus* is a Latin word that means "jointed."

Virga, also called fallstreaks, is a wispy veil that is seen beneath the base of a cloud, but that does not reach to the ground. It is PRECIPITATION falling from the cloud into relatively dry air, where it evaporates. Air currents may carry water vapor from the evaporation of virga aloft to a height where it condenses once more. Virga may consist of water droplets or ice crystals, depending on the type of cloud from which it falls.

A wall cloud is the extension to a cumulonimbus cloud that appears when a mesocyclone has developed inside the cloud and it may be expanding downward to become a tornado. The wall cloud descends below the cloud base. It rotates cyclonically (*see* CYCLONE) and no precipitation falls from it. Although the wall cloud appears to be an extension of the main cloud, in fact it marks the region where warm, moist air is being drawn into the main updraft of the SUPERCELL. The warm air cools adiabatically as it rises, causing some of its moisture to condense, and strong convergence (*see* STREAMLINE) makes it rotate.

A warm cloud is one in which the temperature is above freezing throughout.

A water cloud is one composed entirely of water droplets. It does not extend above the FREEZING LEVEL and therefore contains no ICE CRYSTALS.

A wall cloud hangs beneath the main storm cloud, rotating cyclonically. When a wall cloud appears, a tornado is imminent.

Whaleback cloud is the name sailors have given to a type of lenticular cloud that is sometimes seen in high latitudes. It forms in strong winds over islands and steep coastal cliffs, and the name refers to the smooth, humped shape of the cloud top.

Further Reading

Hamblyn, Richard. *The Invention of Clouds.* New York: Farrar, Straus, and Giroux, 2001.

cold pole One of the places that experience the lowest mean temperatures on Earth. The cold poles do not coincide with the geographic North or South Poles. Water movements transport heat through seawater and through pack ice (*see* SEA ICE). Consequently, the climates of coastal areas and islands are strongly influenced by the adjacent sea. There is no land at the geographic North Pole and so its climate is of the maritime type (*see* CLIMATE TYPES). Winters are colder in places with continental climates so, although summers are also warmer, in polar regions the annual mean temperature is likely to be lower over a continental landmass than over an island, coastal region, or the ocean. The geographic South Pole lies close to the center of the large continent of Antarctica, and its climate is, therefore, continental, but the geographic and cold poles still do not coincide.

Surface atmospheric pressure is permanently high over both polar regions, but the centers of these high-pressure cells are some distance from the geographic poles and over landmasses. Air is subsiding and diverging and often there is a temperature INVERSION below a height of about 3,300 feet (1,000 m). Above the inversion air is diverging. The cells are not strong features, but they intensify the CONTINENTALITY, and it is this that produces extremes of temperature.

In the Southern Hemisphere, the cold pole is at the VOSTOK STATION, where the temperature on July 21, 1983 was -128.6°F (-89.2°C). This is the lowest surface temperature that has ever been recorded anywhere on Earth. It was exceptional, of course. August is usually very slightly colder than July at Vostok, with an average temperature of -89.6°F (-67.6°C). The annual mean temperature at Vostok is -67.1°F (-55.1°C). The annual mean temperature at the Scott–Amundsen Station, close to the geographic South Pole, is -55°F (-48°C). Vostok also experiences a wide temperature range. In January, which is the warmest month of the Antarctic summer, the average temperature at Vostok is -25.7°F (-32.1°C). At the South Pole, the temperature range is much smaller, from an average -61°F (-51°C) in winter to -55°F (-48°C) in summer.

The Northern Hemisphere cold pole is at Verkhoyansk, Siberia, at 67.57°N 133.85°E. Verkhoyansk is much farther from the geographic pole than Vostok, because there is no continental landmass at the pole itself. Its mean annual temperature is 1.1°F (-17.2°C). January is the coldest month, when the mean temperature is -58.5°F (-50.3°C), but the lowest temperature ever recorded at Verkhoyansk is -89°F (-67°C). Summers are warm, however. In the warmest month, July, the mean temperature is 56.5°F (13.6°C). This is the average of daytime and nighttime temperatures, and the mean daytime temperature is 66°F (19°C), the highest ever recorded being 98°F (37°C).

There are two continents in the Northern Hemisphere, Eurasia and North America. This means there is also a cold pole in North America. It is at Snag, Yukon, in northwestern Canada, at about 62.37°N 140.40°W. In February 1947, the temperature at Snag airport fell to -81°F (-63°C). This is the lowest temperature ever recorded in North America. January is usually the coldest month, when the average temperature is -18.5°F (-28.1°C). The mean annual temperature is 21.6°F (-5.8°C). July is the warmest month. Then the mean temperature is 57.0°F (13.9°C).

Elevation affects temperature. Vostok Station is 11,401 feet (3,475 m) above sea level, the elevation of Verkhoyansk is 328 feet (100 m), and that of Snag is 1,925 feet (587 m). When these differences are taken into account, the temperature differences between the three cold poles becomes less marked.

cold wave A sudden and large drop in temperature. Although cold waves happen throughout the middle latitudes, it is only in the United States that they are defined precisely. Over most of the United States a cold wave is defined as a temperature decrease of at least 20°F (11°C) that occurs over a period not exceeding 24 hours and reduces the temperature to 0°F (-18°C) or lower. In California, Florida, and the Gulf Coast states, the temperature drop must be of at least 16°F (9°C) to a temperature of 32°F (0°C) or lower. On average, three or four cold waves affect the United States every winter.

Cold waves are responsible for more deaths than any other weather phenomenon of middle latitudes. They are caused by the undulations in the polar front JET STREAM that develop toward the end of the index cycle (*see* ZONAL INDEX). As the undulations extend southward, polar air follows, behind the polar FRONT. Pressure is low in the wave and the circulation around the edges of the TROUGH is cyclonic (*see* CYCLONE). Cyclonic circulation draws air from the far north southward along the western side of the trough, making this the colder side. Cold waves can bring Canadian winter temperatures as far south as the Gulf of Mexico. Cold waves are shallow, especially over the central and southern states, where they seldom extend higher than about 3,000 feet (900 m).

colloid Two homogeneous substances in different phases (solid and liquid, solid and gas, or liquid and gas) that are thoroughly mixed together. A cloud is a colloid consisting of water droplets (liquid) distributed in air (gas).

CLOUD DROPLETS aggregate into larger RAINDROPS due to a property of clouds known as colloidal instability.

Colorado low An area of low pressure that sometimes develops on the eastern slopes of the Rocky

Mountains, in the state of Colorado. Air passing over the mountains develops a cyclonic circulation (*see* CYCLONE) and then the system moves eastward, bringing storms with heavy precipitation. It is similar to the ALBERTA LOW.

combustion A chemical reaction in which an element combines rapidly with oxygen and energy is released in the form of heat, light, or both. Certain elements, such as sodium and uranium, are oxidized spontaneously as soon as they are exposed to the oxygen in air, and burn with a brilliant flame. Other substances must be heated before they will ignite. All of the materials that are burned as fuel are of this type (uranium, plutonium, and other fuels used in nuclear reactors are not burned; they do not release energy through combustion). The fuels that are burned include petroleum, natural gas (primarily methane), coal, peat, wood, and other plant material. The key ingredients in all of them are hydrocarbons, which are compounds of carbon (C) and hydrogen (H). These are oxidized to CARBON DIOXIDE (CO_2) and water vapor (H_2O) with the release of energy:

$$C_xH_y + O_2 \rightarrow CO_2 + H_2O + \text{energy}$$

When a fuel is heated, for example by applying a match to it, some of the hydrocarbons are vaporized. Among the molecules of the hydrocarbon vapor there are some that react with oxygen molecules. That reaction releases energy, some of which is absorbed by other hydrocarbon molecules. The additional energy makes the molecules move faster and increases the violence of the impact when two molecules collide. Some of the collision impacts are violent enough to break a molecule into smaller molecules or atoms, producing IONS or free radicals, which are groups of atoms with unpaired electrons. Ions and free radicals are highly reactive, and combine rapidly with gas molecules. This facilitates the oxidation of those molecules, releasing more ions and free radicals. The result is a chain reaction, in which the oxidation of one molecule accelerates the oxidation of others. Once the reaction has commenced it advances very rapidly like a wave, moving in all directions.

As atoms absorb the energy that is released by oxidation, some of their electrons are excited, which means they jump to higher energy levels (orbitals). Then they fall back to their previous level. As it drops to a lower orbital, each electron emits the energy it absorbed as a photon of light. When large numbers of photons are emitted, they are visible as a flame. The wavelength (*see* WAVE CHARACTERISTICS) of the light that the electrons emit is proportional to the amount of energy being absorbed and released. Consequently, the color of a flame is an indication of its TEMPERATURE.

Hydrocarbons will burn only if they are mixed with air in the correct proportions. Gas may not burn at all at the center of a flame, because there is insufficient oxygen to sustain combustion. The edge of a flame marks the boundary where there is too little fuel to sustain combustion. One consequence of this is that combustion does not consume all of the fuel. Except in very efficient industrial incinerators, the combustion of fuel releases unburned hydrocarbons into the air. These may condense to form soot particles (*see* AIR POLLUTION), which consist mainly of carbon, or they may participate in further reactions that lead to the formation of PHOTOCHEMICAL SMOG.

Although carbon dioxide and water are the only products of the combustion of hydrocarbons, hydrocarbons in fuels are attached to a large variety of other substances, some of which also burn. Sulfur, for example, is oxidized to SULFUR DIOXIDE. If combustion generates high enough temperatures and pressures, as it does in modern car engines, atmospheric NITROGEN is oxidized, releasing NITROGEN OXIDES. Other components of fuel do not burn. These are vaporized, but the vapor quickly condenses into fine, solid particles of ash that may contain traces of many elements, including metals.

The combustion of hydrocarbons is undoubtedly a convenient way to obtain energy, but it is also by far the largest cause of air pollution. Natural FIRE also causes serious pollution.

Further Reading

Allaby, Michael. *Fog, Smog, and Poisoned Rain.* New York: Facts On File, 2003.

comfort zone The range of TEMPERATURES within which humans feel comfortable. For most people this is between about 65°F (18°C) and 75°F (24°C). Adjustments have to be made at temperatures higher or lower than these. People add or remove layers of clothing, light fires, turn the heating up or down, sweat, or shiver.

Wind and relative HUMIDITY can make the air feel warmer or colder than it really is. Wind carries warm air away from the body and causes windchill, which can be harmful in cold weather.

Effective temperature is the concept used to define comfort zones. The effective temperature is the temperature of saturated air, with an average wind speed of no more than 0.45 MPH (0.2 m/s), that would produce the same sensation of comfort in a sedentary person wearing ordinary indoor clothes as air with the actual movement, humidity, and temperature to which that person is exposed. Effective temperature is approximately equivalent to the temperature–humidity index. The term is also used to describe the temperature of the surface of a planet in the absence of an atmosphere. The effective temperature on Earth is approximately -0.4°F (-18°C). This is lower than the actual temperature, largely because of the greenhouse effect.

The temperature that the body feels is known as the sensible temperature. This is not always the same as the air temperature measured by a thermometer, because the sensation of heat or cold is affected by several factors in addition to the actual temperature of the air. These include the wind, the rate at which the body loses heat through conduction, convection, and radiation from exposed skin surfaces, from the evaporation of sweat, and from the respiratory tract (which is exposed to inhaled air that is below body temperature). Several of these, and especially the rate of evaporation from the skin, are related to the relative humidity (RH) of the air. When the air is warm, a high relative humidity can make the temperature feel higher than it is. This is because the high humidity reduces the rate at which sweat can evaporate from the skin. Latent heat for the vaporization of sweat is taken from the skin surface. This cools the skin and helps maintain a constant body temperature. If evaporation is restricted in hot weather, people feel uncomfortable and talk of the air feeling “close,” “sticky,” or “oppressive.” At very high temperature and humidity, this can be dangerous to health.

When the humidity is low, the air can feel warmer than it really is in winter and cooler than it really is in summer. This can also be dangerous. A fine, sunny day can feel pleasantly warm despite the temperature being far below freezing. Frostbite can occur unless the face, ears, fingers, and toes are kept adequately protected. Similarly, the temperature may be high enough on what feels like a pleasantly cool day in summer to cause heat stroke in people who remain exposed to the heat for too long.

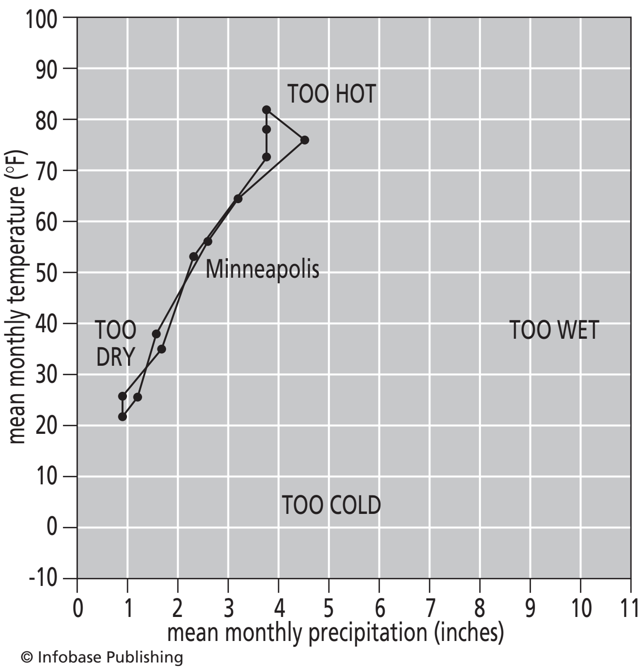
When the temperature is low, the body does not sweat, but heat is lost by conduction to the air in contact with the skin, making the temperature feel lower than it really is. Sensitivity to these effects vary from one person to another, and people acclimatize to those weather conditions to which they are most often exposed, but which may feel uncomfortable to a person who is newly arrived.

Sensible temperatures are used in conjunction with RH to define comfort zones. These can be shown graphically on a chart that plots temperature against precipitation. When the resulting comfort chart is overlaid with a hythergraph it shows at a glance whether or not the climate of a particular place is likely to prove comfortable.

In 1979, R. G. Steadman of the National Weather Service calculated the effect of humidity on apparent temperature and used this to produce an index of heat stress. The index sets out the relationship between the actual temperature, relative humidity, and apparent temperature. When the actual temperature is 95°F (35°C) and the relative humidity is 50 percent, for example, the temperature will feel as though it is a very uncomfortable 107°F (42°C). If the relative humidity is only 10 percent, on the other hand, the apparent temperature will be 90°F (32°C) and there is a dan-

temp.	*relative humidity (%)*									
°F (°C)	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
80 (27)	75	77	78	79	81	82	85	86	88	91
85 (29)	80	82	84	86	88	90	93	97	102	108
90 (32)	85	87	90	93	96	100	106	113	122	
95 (35)	90	93	96	101	107	114	124	136		
100 (38)	95	99	104	110	120	132	144			
105 (40)	100	105	113	123	135	149				
110 (43)	105	112	123	137	150					
115 (46)	111	120	135	151						

The chart shows whether a particular combination of temperature and humidity will produce physical discomfort. Read the actual temperature in the left column and follow that row to the right to the column directly below the relative humidity, indicated in the row along the top of the chart. The number in the box is the *apparent temperature.* Below 80°F (27°C), there is no risk to most people. At 80°–90°F (27°–32°C), caution should be exercised. The range 106°–130°F (41°–54°C) is dangerous; temperatures higher than 130°F (54°C) are extremely dangerous.



The "comfort chart" plots sensible temperature and humidity and overlays a hythergraph for Minneapolis.

ger people might remain in the open for rather longer than they would if the air were moister, which could be harmful to them.

The National Weather Service categorizes apparent temperatures according to the heat stress they impose. It recognizes four categories: Caution; Extreme caution; Danger; and Extreme Danger.

Below an apparent temperature of 80°F (27°C), there is no risk to most people.

Caution: At an apparent temperature of 80–90°F (27–32°C), caution should be exercised. Prolonged exposure to this range of apparent temperature combined with physical activity may cause fatigue in some people.

Extreme caution: At an apparent temperature of 90–106°F (32–41°C), extreme caution should be exercised. Prolonged exposure combined with physical activity can cause sunstroke, heat cramps, and heat exhaustion.

Danger: An apparent temperature of 106–130°F (41–54°C) is dangerous; prolonged exposure combined with physical activity are likely to cause sunstroke, heat cramps, or heat exhaustion, and heat stroke may occur.

Extreme danger: An apparent temperature in excess of 130°F (54°C) is extremely dangerous. Sunstroke and heat stroke are likely to occur after quite short exposure.

The temperature–humidity index (THI), also called the comfort index, discomfort index, or heat index is a numerical value that relates the temperature and humidity of the air to the conditions that will make a sedentary person wearing ordinary indoor clothes feel comfortable. It is calculated by:

$$\text{THI} = 0.4(T_a + T_w) + 15$$

where T_a and T_w are the dry-bulb temperature and wet-bulb temperature (*see* TEMPERATURE) respectively, measured in °F. If the temperatures are measured in °C the equation is:

$$\text{THI} = 0.4(T_a + T_w) + 4.8$$

compressional warming The mechanism by which a fluid warms when it is compressed. Compression means that the volume of the body of fluid is reduced and, therefore, that the molecules comprising the fluid move closer together. This happens because they have been pushed into a small space by molecules in the surrounding fluid.

When molecules collide, KINETIC ENERGY is transferred from one to another. If the colliding molecules remain within the same body of fluid and at a constant TEMPERATURE, the amount of kinetic energy remains unchanged, because no energy is lost in the transfer of energy between molecules. In a contracting fluid, however, the molecules in one body of fluid (in the surrounding fluid) transfer kinetic energy to molecules in a different body of fluid (the contracting fluid). Consequently, energy leaves the surrounding fluid and is absorbed into the body of fluid undergoing compression. The gain of kinetic energy means that the molecules move more rapidly. When they collide with a surface, such as that of the bulb of a THERMOMETER or of heat sensors in human skin, the impact is more violent than it was formerly. This is measured by the thermometer and felt by the skin as a rise in temperature. The opposite happens when a fluid expands. This is known as EXPANSIONAL COOLING.

computer Literally, any device that performs mathematical calculations (i.e. computations). An electronic computer accepts data fed into it in a prescribed form, processes that data, and supplies the results of its computations either by displaying them on a screen or printing them, or by sending them directly to another machine or feeding them into another process.

Because electronic computers operate at great speed, they are widely used by meteorologists to perform the many calculations that are required to prepare weather forecasts (*see* WEATHER FORECASTING). Climatologists use computers to construct the climate MODELS of the atmosphere with which they study past, present, and future climates.

The Electronic Numerical Integrator and Calculator (ENIAC) was the first fully electronic computer. It was built at the University of Pennsylvania by J. P. Eckert and J. W. Mauchly and was completed in 1946. ENIAC comprised 20 electronic adding machines and contained 18,000 thermionic valves. It consumed 100 kW of power when it was at its maximum output. Programming it involved setting switches and plugging in connections manually.

condensation The change of PHASE in which a gas is transformed into a liquid. Gases condense when they saturate the air (*see* SATURATION). The relative HUMIDITY (RH) of the air is then 100 percent with respect to the vapor. Water is the only common substance that exists in all three phases (gas, liquid, and solid) at the TEMPERATURES found at the surface of the Earth and in the troposphere (*see* ATMOSPHERIC STRUCTURE).

RH varies with temperature. In warm air, water molecules have more energy to move freely through the air and so the partial pressure (*see* AIR PRESSURE) of WATER VAPOR is higher in warm air than it is in cold air, where molecules have less energy. As the air temperature falls, the partial pressure approaches the SATURATION VAPOR PRESSURE.

Water vapor condenses when the RH approaches 100 percent provided there is a surface onto which it can do so. The phase change consists of water molecules joining together to form small groups in which the individual molecules are linked by hydrogen bonds (*see* CHEMICAL BONDS). If the vapor condenses onto the ground or surface vegetation, the liquid is called DEW, or FROST if it then freezes or if it changes directly from the gas to the solid by DEPOSITION.

Above the surface, the condensation of water produces CLOUD DROPLETS. Droplets form around very small particles, called CLOUD CONDENSATION NUCLEI. The first droplets to form are very small. They consist of water that merges with hygroscopic nuclei or that condenses onto particles with surfaces that attract water, called wettable aerosols. Tiny droplets then grow as more water condenses onto them and as droplets collide and coalesce.

In the absence of a suitable surface, water vapor will not condense until the RH reaches about 101 percent. The air is then said to be 1 percent supersaturated (*see* HUMIDITY). ICE CRYSTALS will form spontaneously by deposition when the temperature falls below -40°F (-40°C). The formation of water droplets or ice crystals by the condensation or deposition of water vapor in the absence of cloud condensation nuclei or FREEZING NUCLEI is called spontaneous nucleation.

Condensation releases LATENT HEAT. This warms the air, and if the condensation is occurring in air that is rising by CONVECTION and cooling adiabatically (*see* ADIABAT), the release of latent heat sustains the convection. This is the mechanism by which cumuliform clouds (*see* CLOUD TYPES) grow. It is important in the development of THUNDERSTORMS and TROPICAL CYCLONES.

The condensation temperature, also known as the adiabatic condensation temperature or adiabatic saturation temperature, is the temperature at which a PARCEL OF AIR will reach saturation if it cools at the dry adiabatic LAPSE RATE.

The convective condensation level is the height at which condensation occurs in a parcel of air that is rising by convection, if the parcel becomes saturated while it is rising through air in which temperature falls at the dry adiabatic lapse rate, and if there is conditional instability (*see* STABILITY OF AIR) above the height at which the parcel becomes saturated.

The altitude at which the temperature of air that is rising and cooling adiabatically falls to the dew point temperature (*see* DEW) is known as the lifting condensation level. At this height the RH reaches 100 percent and water vapor will start to condense into droplets. The lifting condensation level therefore marks the height of the CLOUD BASE. As the air continues to rise above this level its rate of cooling changes from the dry adiabatic lapse rate to the saturated adiabatic lapse rate.

The mixing condensation level is the lowest height at which water vapor condenses in a layer of air that is thoroughly mixed. Vertical mixing of the air averages the temperature and MIXING RATIO throughout the mixed layer and the mixing condensation level occurs where the POTENTIAL TEMPERATURE is equal to the dew point temperature of the mixed air.

Condensation that occurs in rising air when the condensation level is higher than the FREEZING LEVEL, so that water vapor changes directly into ice by deposition, is called the snow stage.

conduction The transmission of heat through a substance from a region that is relatively warm to another region that is relatively cool until both are at the same temperature. In a fluid (gas or liquid) the heat is transferred by collisions between atoms or molecules. When atoms or molecules with higher KINETIC ENERGY collide with atoms or molecules having lower kinetic energy, a proportion of the energy is transferred; the atom or molecule with lower kinetic energy gains energy and the atom or molecule with higher kinetic energy loses energy. In this way energy is exchanged until all the atoms or molecules possess the same energy.

TEMPERATURE is a measure of the kinetic energy of atoms and molecules, so a transfer of kinetic energy implies a redistribution of temperature. Conduction is one of the three ways in which heat is transmitted. The others are CONVECTION and radiation.

A large body of air that is at the same temperature throughout is said to be in isothermal equilibrium, also called conductive equilibrium. Isothermal equilibrium develops if the air remains unaffected by conditions external to itself for long enough to allow the temperature to equalize by conduction.

The rate at which heat passes through a substance is known as the thermal conductivity of that body. Thermal conductivity is measured as the amount of heat that is transmitted in unit time over a unit distance in a direction perpendicular to a surface of unit area under conditions in which the transfer of heat depends only on the temperature gradient. It is measured in units of joules per second per meter per kelvin (J/s/m/K), or British thermal units per second per foot per degree Fahrenheit (Btu/s/ft/°F); 1 J/s/m/K = 5.598 Btu/s/ft/°F.

The thermal conductivity of dry sand is 0.3 J/s/m/K (1.68 Btu/s/ft/°F), of wet sand 2.2 J/s/m/K (12.32 Btu/s/ft/°F), and of water 0.561 J/s/m/K (3.14 Btu/s/ft/°F).

The rate at which heat penetrates a material is called the thermal diffusivity of that material. It depends on the thermal conductivity of the material, its density, and its specific HEAT CAPACITY. Thermal diffusivity (κ) is given by:

$$\kappa = k/\rho C$$

where k is the thermal conductivity, ρ is the density, and C is the specific heat capacity. Thermal diffusivity is measured in square meters per second.

Thermal resistivity is the opposite of thermal conductivity. It is a measure of how poorly a material conducts heat.

Thermal diffusivity (κ) of common materials

quartz	0.0000044
dry sand	0.0000023
wet sand	0.0000074
clay	0.0000015
still water	0.00000014
still air	0.00002

continental drift The theory that the continents have not always occupied the positions in which they are seen today and that they are still moving across the Earth's surface. The German meteorologist Alfred Wegener (1880–1930; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) was the first scientist to propose this idea in its modern form. In his book *Die Entstehung der Kontinente und Ozeane* ("The Origin of the Continents and Oceans"), first published in 1915, Wegener described what he called "continental displacement." The South African geologist Alexander Logie Du Toit (1878–1948) was the first person to use the term *continental drift*. Du Toit had found many similarities in the rock formations of South Africa and South America. This led him to support Wegener's theory. His book, *Our Wandering Continents: An Hypothesis of Continental Drift,* appeared in 1937.

It was not a new idea. Many people had noticed the apparent fit between the coastlines of the continents on either side of the Atlantic Ocean. The Dutch cartographer Abraham Ortelius (1527–98) suggested in 1596 that the continents had once been joined, but they had been torn apart by earthquakes and floods. In 1881, at a time when many scientists believed that the Moon had been torn away from the Earth, the English geologist Osmond Fisher (1817–1914) suggested that the Pacific Ocean filled the scar this had made. As Asia and America moved closer together to heal the scar, Fisher proposed that America was torn from Africa and Europe and the Atlantic opened between them.

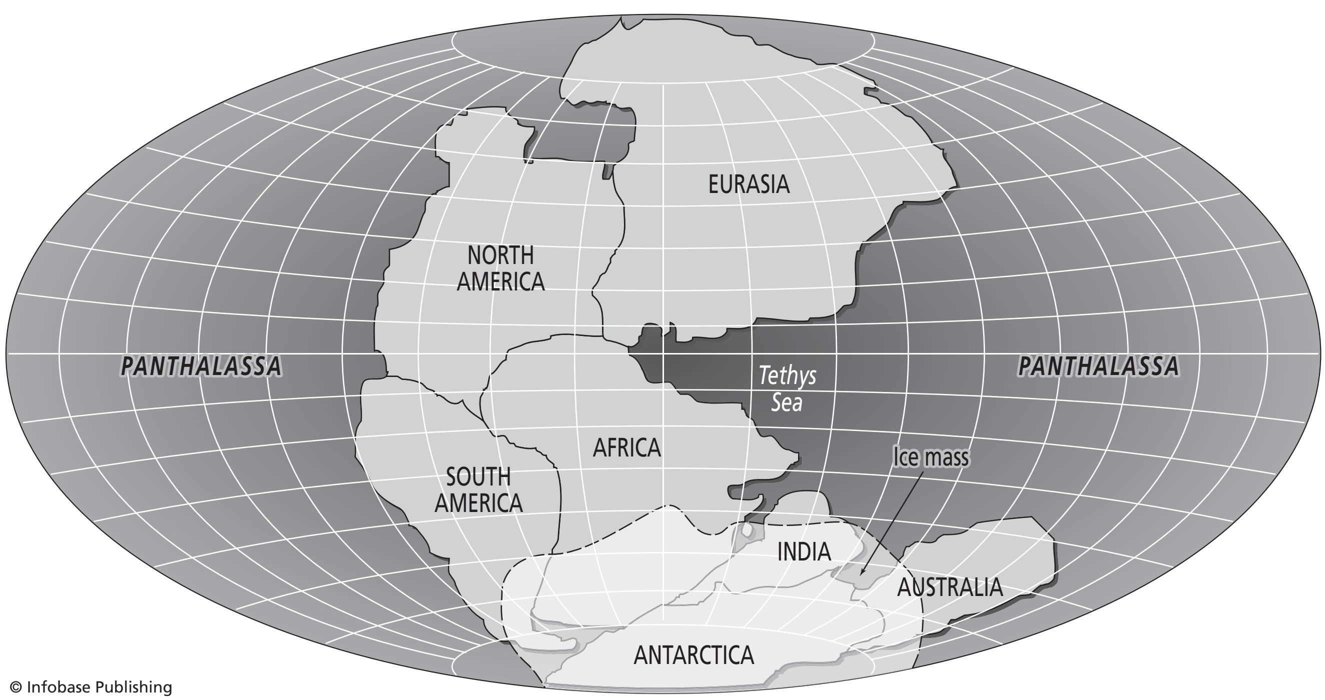
Wegener noted that the Appalachian Mountains of North America matched the mountains of the Scottish Highlands, and that American coal deposits matched coal deposits in Europe. Similar fossils occurred on both continents and there were fossils of tropical plants in Spitzbergen, suggesting that the climate in that part of the Arctic had once been tropical.

Measurements of the longitude of Greenland suggested to Wegener that over the course of a century Greenland had moved away from Europe by about one mile (1.6 km). It also seemed that Washington D.C. and Paris were moving apart by about 15 feet (4.6 m) a year and that San Diego, California, and Shanghai, China, were moving toward each other by about 6 feet (1.8 m) a year. Unfortunately, the measurements were incorrect, and this helped to discredit Wegener's theory. Accurate measurements have since found the continents are moving at about one-tenth the speed that he supposed.

Wegener assembled the evidence and then joined coastlines together where they seemed to fit. He concluded that about 300 million years ago all the continents had formed a single supercontinent, which he called Pangaea, a word meaning "all Earth" (from the Greek *pan,* "all," and *ge,* "Earth"). A single ocean, Panthalassa, which means "all sea," surrounded Pangaea. Then Pangaea started to break apart and its sections, forming the present continents, moved away from one another. South America and Africa began to separate around 150 million years ago, and Australia and Antarctica separated about 40 million years ago.

In his book, Du Toit proposed that the southern continents had once been joined in a supercontinent he called Gondwanaland, and the northern continents had comprised Laurasia. As Pangaea began to split, an arm of the ocean separated them. This was called the Tethys Sea. The Mediterranean Sea is a remnant of Tethys. It was not until the 1960s that the theory of continental drift won full scientific acceptance. It has now been incorporated in the larger theory of PLATE TECTONICS.

continentality The extent to which the climate of a particular place resembles the most extreme type of continental climate (*see* CLIMATE TYPES). Although climates can be broadly classified as continental or maritime, these types grade from one into the other. Except on ocean islands and some, but not all, coasts, a place



Pangaea as it is believed to have existed about 200 million years ago, when the supercontinent had begun to break apart and the Tethys Sea separated the northern and southern regions.

with a maritime climate also experiences more continental weather conditions for some of the time. Similarly, maritime influences extend a long way inland from the coasts of continents.

There is a need to refine the classification of continental and maritime climates in a way that reflects the gradations between them. The differences can be shown clearly on a HYTHERGRAPH, but only in a relative sense. The hythergraph compares the climates of two or three places (including more makes the graph too cluttered to be easily read), but gives no absolute value for the continentality of their climates. This is possible if the essential climatic features of an area, together with its latitude, can be used to calculate an index of continentality.

A simple way to achieve this is to note the extent to which the area lies beneath continental air (*see* AIR MASS). In 1940, the German climatologist H. Berg proposed a method based on this principle. If the frequency with which continental air masses lie over an area is related to the total number of air masses of all kinds in the course of a year, the result can be shown as a percentage:

$$K = (C/N) \times 100$$

where K is the index of continentality, C is the number of continental air masses that covered the area in the year, and N is the total number of air masses covering the area during the same period. Because it calculates percentages, an extreme maritime climate has a continentality index of 0 percent and an extreme continental climate has an index of 100 percent.

This index shows that continentality is only about 25 percent over most of Norway, all of Denmark, and Europe west of about 5°E longitude, a region that includes all of France lying to the west of Paris and the whole of Spain and Portugal. The index falls to only 50 percent at about 20°E. In Scandinavia the change from maritime to continental climates is abrupt, because of mountains that obstruct the eastward flow of maritime air. Elsewhere in western Europe, where there are no mountain ranges, the transition is much more gradual.

The index is easy to understand, but in order to calculate it, it is necessary to record the types of air mass. This means accurately checking the movements of air masses over several years in order to obtain an average. It is much more complicated than using the annual temperature range (*see* TEMPERATURE) as the key datum. Accurate temperature records are kept for most places and they are readily available. The more continental the climate the greater the temperature range will be. Allowance must be made for latitude, because this affects the amount and seasonal distribution of solar radiation.

Several attempts have been made to devise a reliable method. The one that is now most widely used was introduced in 1946 by the American climatologist V. Conrad. According to the Conrad formula:

$$K = 1.7\, A/\sin(\text{ø} + 10) - 14$$

where A is the average annual daytime temperature range and ø is the latitude. The Conrad index should yield a value of 0 for a fully maritime climate and 100 for a fully continental climate. Thorshavn in the Faeroe Islands has an index of -2.5 and Verkhoyansk, in Siberia, has an index of 103. In North America, values for K range from 0 to about 10 along the western coast and are between 30 and 40 in New England. In the central United States, the values are generally between 60 and 65, but higher in some places. The value for Omaha, Nebraska, is 76.

The production of extreme temperatures in summer and winter in water that is almost completely surrounded by a continental landmass is called the continentality effect. This produces a continental climate in places that would otherwise experience a maritime climate owing to their proximity to an ocean. Hudson Bay, in northern Canada, is fully ice-covered in winter owing to this effect, despite being farther south than parts of the Atlantic and Pacific Oceans that are free from ice. (Fort Severn, Ontario, on the shore of Hudson Bay, is at 56.97°N; Dundee, Scotland, is at 56.50°N.)

Further Reading

Conrad, V. "Usual formulas of continentality and their limits of validity." *Transactions of the American Geophysical Union,* vol. 17, 663–664.

contrail **(condensation trail, vapor trail)** A long, narrow cloud that is produced by the exhaust from an aircraft engine. Exhausts from piston engines can produce contrails, but they are more often associated with jet aircraft. This is partly because jet engines burn more fuel than piston engines and consequently emit larger quantities of WATER VAPOR, and partly because jet aircraft fly at higher altitudes, where contrail formation is more likely.

The water vapor is a product of the COMBUSTION of gasoline and kerosene. These are hydrocarbons (containing hydrogen and carbon) and combustion is the oxidation of carbon (C) and hydrogen (H) in an exothermic (energy-releasing) reaction.

$$C + O_2 \rightarrow CO_2 \text{ and } 4H + O_2 \rightarrow 2H_2O.$$

The hot, moist, exhaust gas is pumped into cold air and immediately starts to cool. Cloud will form if sufficient CLOUD CONDENSATION NUCLEI (CCN) are present and the mixture of air and gas cools to below its DEW point temperature. Engine exhausts release particles of unburned fuel and soot that act as CCN, so cloud will form provided the air reaches SATURATION. This is unlikely in the lower part of the troposphere (*see* ATMOSPHERIC STRUCTURE) when the sky is clear, because the temperature is high enough for the water vapor in the exhaust to be absorbed without saturating the air. At high altitude, however, the air is very cold and therefore soon saturated.

Most contrails form above 20,000 feet (6,000 m), but the precise altitude at which they form varies from day to day. They are usually composed of ICE CRYSTALS. It takes a few seconds for the exhaust gases to cool to the dew point temperature, which is why contrails begin a short distance behind the airplane producing them. Usually, high-level winds quickly disperse contrails by mixing the cloud with drier surrounding air until the relative HUMIDITY of the mixture falls below 100 percent and the ice crystals sublimate (*see* SUBLIMATION). If the upper air is close to saturation, contrails survive for much longer and spread into cirrus or cirrostratus cloud (*see* CLOUD TYPES).

Contrails that remain visible for an hour or longer indicate the presence of moist air aloft. This is probably air in the warm sector of an approaching frontal system (*see* FRONT), which means the amount of cloud is likely to increase and PRECIPITATION will commence in a few hours. Where the air traffic is heavy, contrails increase cloudiness by an appreciable amount.

A contrail-formation graph can be drawn to determine the height at which contrails will form. This is a graph on which AIR PRESSURE, TEMPERATURE, and relative humidity are plotted. Calculating this height is of military importance, because contrails make high-altitude aircraft clearly visible.

control day A day on which folk custom holds that the weather will determine the weather over the coming weeks, months, or season. Many control days are associated with Christian saints or festivals.

The weather on Easter Day and Christmas Day are believed to be linked:

Easter in snow, Christmas in mud,
Christmas in snow, Easter in mud.

Candlemas, on February 2, is the festival that is traditionally celebrated with lighted candles; it is the day on which Simeon recognized Jesus as "A light to lighten the Gentiles, And the glory of thy people Israel" (Luke, 2, 32). According to English weather lore, it is the day when the state of the weather indicates whether winter has ended. It is an English equivalent of Groundhog Day (*see* WEATHER LORE). It is also a day by which it is said that a farmer should still have half of his hay and straw safe in the barn, because it will be some time before his animals can be grazed outdoors. One of several versions of the belief:

If Candlemas be fair and bright,
Winter'll have another flight.
But if Candlemas Day be clouds and rain,
Winter is gone and will not come again.

Christmas Day is believed to indicate what the weather will be like in the following months. If Christmas Day is fine, the spring will be mild, there will be no frosts in May, and therefore there will be a good crop of tree fruit in the fall.

Easter Day is believed to indicate what the weather will be like in the following months. One tradition holds that

Easter in snow, Christmas in mud
Christmas in snow, Easter in mud.

Another saying is that rain on Easter Day means June will be a wet month:

If it rains on Easter Day,
There shall be good grass but very bad hay.

Rain will make the grass grow well, but after mowing the grass must dry thoroughly if it is to make good hay.

Saint Bartholomew's Day falls on August 24.

If Saint Bartholomew be fair and clear,
Then a prosperous autumn comes that year.

Saint Hilary's Day falls on January 13. According to a folk belief, this is the coldest day of the year and so the rest of the winter will be warmer.

Saint Mary's Day falls on July 2. If it rains on this day the rain will continue for a further month.

Saint Michael and Saint Gallus are a pair of control days that fall on September 29 and October 16 respectively.

If it does not rain on Saints Michael and Gallus,
The following spring will be dry and propitious.

Saint Paul's Day falls on January 25.

If Saint Paul's Day be fair and clear,
Then it betides a happy year.

Saint Simon and Saint Jude are celebrated on October 29. This is the day when the weather is bad and possibly dangerous, with gales and storms at sea.

Saint Swithin's Day, on July 15, is possibly the most famous of all control days. The weather on this day will continue for a further 40 days.

Oh Saint Swithin if thou'll be fair,
For forty days shall rain nae mair,
But if Saint Swithin's thou be wet,
For forty days it raineth yet.

The belief arose because prior to his death in 862, Swithin, bishop of Winchester, expressed a wish to be buried in the churchyard (ordinarily a bishop would be buried inside the cathedral) so that the rain might fall upon his grave. Later, Swithin was canonized and the canonization ceremony was arranged for July 15, 964. When the monks tried to exhume his body in order to take it into the cathedral for the ceremony, the legend asserts that it rained and that it continued to rain for 40 days, so the canonization had to be postponed. It was eventually carried out, and Swithin was finally interred inside the cathedral. Checks on weather records have found no correlation between rain on July 15 and the weather over the following 40 days, and very little is known reliably about Swithin.

Saint Vitus's Day falls on June 15.

If Saint Vitus Day be rainy weather,
It will rain for thirty days together.

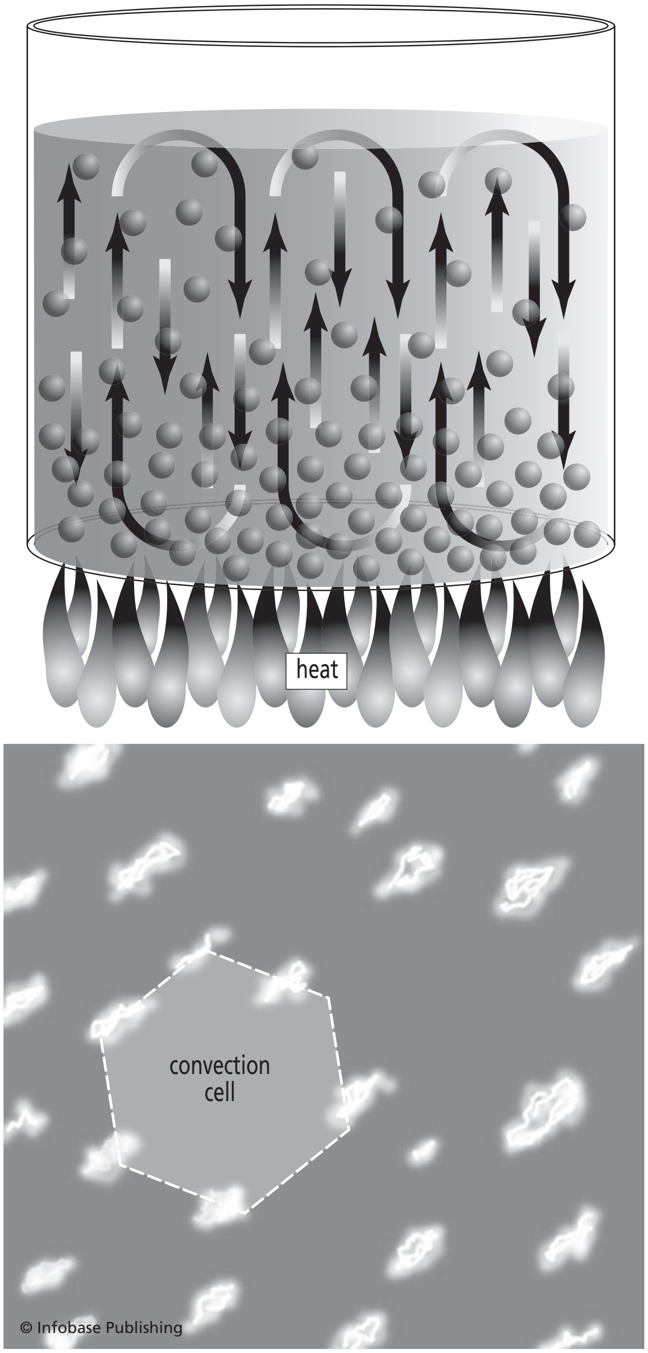
convection Transport of heat that occurs through vertical motion within a fluid. Convection is one of the three processes by which heat is transported from one place to another (the other two are CONDUCTION and radiation). Convection occurs only in fluids, because molecules must be free to move in relation to each other. It is the mechanism that drives the GENERAL CIRCULATION of the atmosphere and the formation of cumuliform clouds (*see* CLOUD TYPES). An area of the land or sea surface above which air is rising by convection, or where convection is especially common, is called a convective region.

A convective circulation is driven by gravity. When a fluid (liquid or gas) is heated from below, the warmed fluid at the bottom expands and becomes less dense. Cooler, denser fluid then descends from above and displaces it. Consequently, the warm fluid rises—effectively it is pushed upward—and its place at the bottom is taken by cool fluid. As the warm fluid rises, it moves away from the source of heat and cools. At the same time, the cool fluid that has sunk to the bottom is warmed. This now becomes warm water, the water that has risen becomes cool water, and they exchange places. This vertical circulation is maintained for as long as heat continues to be supplied at the bottom or, if the fluid is a liquid, until the whole of the liquid has vaporized.

Convective circulation, in which warm air rises, cools, and subsides again, forms a convection cell. Individual atmospheric convection cells cover a fairly small horizontal area, from about 12 to 125 miles (20–200 km) in diameter, but they often occur in large groups, together occupying a large area. Columns of rising and descending air possess opposite VORTICITIES that may repel each other, keeping the columns separate.

Convection cells may be open or closed. An open cell appears as a patch of clear sky that is surrounded by an approximately hexagonal pattern of cumulus clouds. A closed cell consists of a hexagonal layer of stratocumulus that is surrounded by clear sky. Closed cells are smaller than open cells, both horizontally and vertically. Open cells are very common over the oceans and also form on the western sides of the subtropical highs, where air is moving eastward and toward the pole and becoming unstable (*see* STABILITY OF AIR). Closed cells are most common on the eastern sides of the subtropical highs, where there is often a shallow inversion caused by subsiding air, and where upwellings lower the temperature of the sea surface.

A convection cell that is drawn out into long, parallel lines by a strong wind near the surface and WIND SHEAR at a high level forms a convection street. Convection streets can extend for 60 miles (100 km) or more over the ocean. Over land they are less regular and shorter, and are usually aligned downwind from sloping ground that faces the Sun and is therefore a good source of thermals.



(Top) As heat is applied at the base, water in the pot is heated at the bottom and expands. Cooler, denser water sinks to replace it. This motion establishes a vertical circulation (Bottom) Convection cells may be open or closed. These are open cells, with clear sky at the center surrounded by cumulus clouds.

The convection theory of cyclones proposes that convection, especially of moist air, can affect a large enough area and be sustained long enough for air that is drawn in at low level to acquire a distinct cyclonic flow. This can lead to the development of a cyclone.

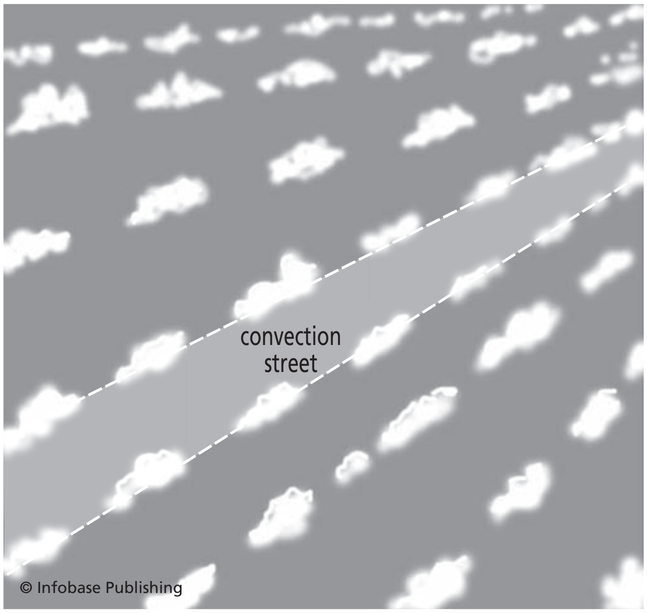
Convection may be free or forced. Free convection is caused by the warming of the air from below. When the temperature of the air is higher than that of the air above it the warm air has positive buoyancy and will rise. Convection does not always arise from heating, however. Forced convection occurs when air that is at the same temperature as the surrounding air, and therefore has neutral buoyancy, is made to rise or sink. This vertical movement can be due to orographic lifting, frontal lifting, or to convergence or divergence (*see* front). The turbulent flow of air across an uneven surface can produce eddies that also cause forced convection. Once the air is moving vertically, it enters regions where the surrounding air is at a different temperature. The air may return to its former level, but it is also possible for convective instability (*see* stability of air) to develop.

A narrow column of air that is rising rapidly by convection and that is enclosed by a much larger volume of air that is rising very little, or that is sinking is known as a hot tower. Hot towers occur widely in the Tropics, and the equatorial air that rises in the Hadley cells (*see* general circulation) does so in the form of many hot towers.

The distance between the surface of the Earth and the height beyond which the vertical motion of air by convection ceases is called the mixing depth. This varies greatly, according to the intensity of convectional motion. Convection mixes the atmospheric constituents, thereby diluting pollutants in a large but variable volume of clean air. Consequently, the greater the mixing depth the better the air quality is likely to be and when the mixing depth is shallow pollutants will concentrate in it. The air below the mixing depth is known as the mixed layer.

Penetrative convection occurs when the ground or water surface is warmer than the air immediately above it. This situation most often develops when cool air moves across a warm surface, and it is especially common in low latitudes. The air is warmed from below, producing conditional instability, which leads to the formation of cumuliform clouds. Unlike the laminar flow and regular cloud patterns produced by cellular convection, penetrative convection produces turbulent flow and is chaotic (*see* chaos).

A thermal is a convection current that forms locally, where the ground has been heated strongly by



Convection streets are parallel lines of cumulus clouds, produced by convection, which extend for many miles over the oceans, although they are shorter over land. The streets often exist even when the air is too dry for clouds to form.

the Sun. As the warm air rises it expands to the sides and drifts downwind. If it reaches its lifting condensation level (*see* CONDENSATION), cumuliform cloud will develop. The condensation of WATER VAPOR will release LATENT HEAT, which will warm the air and generate another thermal that produces castellanus cloud.

Circling in the rising air of a thermal in order to gain height with the minimum expenditure of energy is called thermal soaring. Many birds, including some gulls, eagles, hawks, swallows, and swifts practise thermal soaring and glider pilots imitate them. Birds and glider pilots must seek the thermals, because in addition to swaying this way and that with the wind, thermals soon dissipate.

A wind shadow thermal is a strong thermal upcurrent that develops in warm, sunny weather wherever turbulent flow greatly reduces the wind speed close to the surface. This occurs, for example, on the LEE side of hills and buildings. Because the wind speed is reduced, a shallow layer of air close to the ground is heated by contact with the surface and rises by convection. A wind shadow thermal can also rise from a field containing a crop of wheat or barley. The crop shelters the area between the ground and the top of the plants, so the air in this layer is warmer than the air above the crop. If a gust of wind bends the plants down, a body of warm air is released and rises convectively.

convective equilibrium (**adiabatic equilibrium**) The condition that is found in a tall column of air which is being mixed predominantly by mechanical processes such as air movements, and by CONVECTION. Because of mixing, any PARCEL OF AIR within the column is at the same temperature and pressure as the air around it. If it is displaced vertically, the parcel expands as it rises and is compressed as it sinks, so it remains at the same temperature and pressure as the surrounding air and the temperature decreases with height at very close to the dry adiabatic LAPSE RATE.

Convective equilibrium also ensures that, despite their different weights, the molecules of atmospheric gases remain mixed and do not separate, and that solid particles present in the air remain evenly distributed. Most of the atmosphere in the turbosphere (*see* ATMOSPHERIC STRUCTURE) is in convective equilibrium. Above the turbopause the air is in diffusive equilibrium (*see* DIFFUSION).

conveyor belt A conveyor belt is a wind that blows up the slope of a FRONT. The warm conveyor belt is a wind that blows at a height of about 3,000 feet (1,000 m) a little way ahead of a cold front at a speed of 55–65 MPH (20–30 m/s). The wind carries air over the warm front and then turns eastward until it is approximately parallel to the front. As it rises up the very shallow slope of the front, the moist air cools adiabatically (*see* ADIABAT) until it is saturated (*see* SATURATION) and stratiform cloud (*see* CLOUD TYPES) forms.

The air continues rising until it merges into the nimbostratus layer associated with the cold front. The cold conveyor belt blows ahead of the warm front, carrying air from the cold sector. At first it blows approximately northwestward, parallel to the front, but then turns anticyclonically (*see* ANTICYCLONE).

The conveyor belt often produces some middle cloud to the northwest of the DEPRESSION. (The directions refer to the Northern Hemisphere and should be reversed for the Southern Hemisphere.)

cooling degree days Cooling degree days are a measure which is used in calculating the amount of power that is needed to cool buildings. It assumes that 65°F

(18°C) is a comfortable temperature and that cooling will be required whenever the temperature rises above that value.

Cooling degree days are registered in degrees Fahrenheit and are counted by subtracting 65°F from the mean temperature day by day. If the temperature rises to 75°F, for example, 10 cooling degree days will be recorded on that day. At the end of the year the cooling degree days for each day are added together to give an annual total. At Great Falls, Montana, there are an average of 350 cooling degree days each year; in Seattle, Washington, there are 200; in Detroit, Michigan, there are 700; and in Miami, Florida, there are 4,000.

Cooperative Holocene Mapping Project (**COHMAP**) COHMAP is a long-term study of the changes that have taken place in the climate over the last 18,000 years. The project began by collecting data based on the distribution of fossil plankton in seabed sediments, POLLEN analysis, and the fossil remains of seeds, leaves, and other material. In the 1980s and early 1990s, these data were used to construct a general outline of climatic changes, which was then used to test the changes indicated by a computer model simulation of the atmospheric changes over the same period. The results of this part of the study have been published on the Web.

The continuation of COHMAP involves improving the model simulations by adding details of oceanic circulation and vegetation processes using data that became available during the late 1990s. This phase of the project is called Testing Earth System Models with Paleoclimatic Observations (TEMPO).

Further Reading

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coreless winter A winter in which the temperature falls to its minimum at the autumn equinox, after which it falls no further. This occurs only in Antarctica. During the autumn months of February and March the temperature falls steadily by almost 1°F (0.5°C) a day, but in most years it decreases very little after the equinox. This unusual phenomenon is believed to occur because the amount of heat the continent loses by radiation during the six months of winter is balanced fairly precisely by the heat that is transported to the continent by winds bringing warm air from higher latitudes.

Coriolis effect (**CorF**) When a body that is not attached to the surface of the Earth moves with respect to the surface, its path is deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The French physicist Gaspard-Gustave de Coriolis (1792–1843; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) was the first person to explain this phenomenon, and it is known as the Coriolis effect. It is sometimes called the Coriolis force, and is usually abbreviated as CorF, because it appears as though the moving body is being pushed to one side. In fact, though, no force is involved. The deflection is entirely due to the rotation of the Earth.

Every 24 hours the Earth completes one rotation on its axis. This means that a point anywhere on the surface travels through 360° at a rate of 15° every hour. The linear speed at which these points travel depends on their latitude, however. The circumference of the Earth at the equator is about 24,881 miles (40,034 km), so a place on the equator is traveling eastward at about (24,881 ÷ 24 =) 1,036.7 MPH (1,668 km/h). A place at latitude 40°N, which is approximately the latitude of New York City and Madrid, Spain, has a shorter distance to cover, because the circumference of the Earth at 40°N is about 19,057 miles (30,662.7 km). People in these cities are traveling at about 794 MPH (1,278 km/h).

Suppose an airplane set off to fly to New York from a point on the equator due south of New York, but the navigator knew nothing about the Coriolis effect and so the airplane headed due north. At takeoff, the airplane is traveling eastward at 1,037 MPH (1,668 km/h). Once airborne and no longer attached to the surface, the airplane continues to move to the east at the same speed. The flight to New York will take 6 hours, during which time the airplane will travel (1,037 × 6 =) 6,222 miles (10,012 km) to the east. New York is also traveling eastward, but at only 794 MPH (1,278 km/h), so during the 6 hours it takes the airplane to make the journey the city will have moved 4,764 miles (7,665 km) to the east. By the time it arrives, the airplane will have traveled (6,222 – 4,764 =) 1,458 miles (2,346 km) farther to the east than New York. Instead of being over the city it will be far out over the Atlantic, not even within sight of land.

This is the Coriolis effect. It makes it seem that the airplane has been pushed far to the east (to the right) of the course its crew intended. For the same reason an airplane traveling in the opposite direction, south from New York, would experience an apparent drift to the west—also a deflection to the right. In reality, of course, navigators allow for CorF and adjust the airplane heading.

CorF also affects bodies traveling east and west. In this case there is no difference in speed between a moving body and the surface beneath it, but the orientation of the surface changes as the Earth rotates. This alters the angle at which a body moving in a straight line crosses the lines of longitude. Again, the result is an apparent deviation to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

The higher the latitude, the greater is the deflection. This is because the lines of longitude converge toward the North and South Poles, so the change in their orientation over any distance is greater than the change in a lower latitude.

The change in CorF magnitude with latitude is given by the Coriolis parameter. This is $2\Omega \sin ø$, where Ω is the angular velocity (*see* VELOCITY) of the Earth (7.29×10^{-5} rad/s) and ø is the latitude. Note that when $ø = 0°$, at the equator, $\sin ø = 0$, and when $ø = 90°$, at the pole, $\sin ø = 1$. Consequently, the magnitude of the CorF is zero at the equator and reaches a maximum at each pole.

CorF also varies according to the speed of the moving body. This is because the faster a body travels the greater the distance it covers in a given time. When this is taken into account, it is simple to calculate the magnitude of the CorF on a body at a given latitude moving at a given speed by $\text{CorF} = 2\Omega \sin øv$, where v is the speed. The result will be an ACCELERATION, because Ω, in units of radians per second, is multiplied by v, in units of meters (or feet) per second, to give a result measured in units of distance (feet or meters) per second per second.

There is no truth in the persistent belief that water flowing out of a bathtub spirals in a counterclockwise direction in the Northern Hemisphere and clockwise in the Southern Hemisphere, and that the spiral reverses direction if the tub is carried across the equator. CorF applies only to movements over a large distance. Water spiraling out of a bathtub is too small a phenomenon to be influenced and although the water spirals out of the tub, the direction of the spiral is largely a matter of chance. Even if it were affected while the tub was in a high latitude, the fact that the CorF parameter is zero at the equator means it would not be affected at the equator.

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corner stream When a wind is blowing through an urban area, a corner stream is air that is deflected around the sides of a tall building situated downwind of a lower building. The wind crossing over the top of the lower building strikes the face of the taller building, producing a stagnation point about three-quarters of the way from its base. Air divides at the stagnation point, some rising over the building and some flowing downward. Some of this air contributes to EDDIES on the LEE side of the lower building, and the remainder travels around the sides of the tall building as corner streams that wrap around the back. As they pass the sides of the tall building, the corner streams blow at a speed about 2.5 times greater than that of the wind as it approaches the buildings.

cosmic radiation A stream of particles possessing high energy that originates in space, some of it outside the solar system, and that falls onto the Earth. Primary cosmic rays consist of nuclei of the commonest elements, predominantly of HYDROGEN; a hydrogen nucleus comprises a single proton. The radiation also includes electrons, positrons (particles identical to electrons, but carrying positive charge), neutrinos, and photons (electromagnetic radiation) at gamma-ray wavelengths of about 0.00001 µm.

As they penetrate the atmosphere, the particles collide with atoms of nitrogen and oxygen. These collisions produce secondary radiation, consisting of more particles and gamma-ray photons. A single cosmic-ray particle is able to generate a large shower of secondary particles. Cosmic radiation contributes to the ionization (*see* ION) of gases that produces the ionosphere (*see* ATMOSPHERIC STRUCTURE).

Cretaceous The third and final period of the MESOZOIC era, which began 145.5 million years ago and ended 65.5 million years ago, when an asteroid struck the Earth, causing the extinction of many animals, including the dinosaurs. Flowering plants became much more widespread and numerous during the Cretaceous, but mammals were small and mainly nocturnal. During the Cretaceous, large amounts of atmospheric CARBON DIOXIDE were incorporated into the shells of marine organisms. When the animals died, their shells sank to the seabed, eventually being transformed into carbonate rocks, such as chalk and limestone. The White Cliffs of Dover, on the south coast of England, were formed at this time.

critical point The temperature above which a gas cannot be liquefied, regardless of the pressure to which it is subjected. Beyond its critical point the gas becomes a supercritical fluid, which is a fluid that has the density of a liquid, but the molecular freedom of a gas. The critical point for water is 705.9°F (374.4°C). At that temperature water vapor will condense into a liquid at a pressure of 220 atmospheres (32,000 lb/in^2, *see* UNITS OF MEASUREMENT).

Cryogenian The third period of the NEOPROTEROZOIC era, which lasted from 850 million years ago until 630 million years ago. There were at least two and possibly as many as four GLACIAL PERIODS during the Cryogenian. Some scientists have suggested that at least one of these ice ages was so severe as to have

Wind striking the face of the tall building divides at a stagnation point. Part of the air flows downward and accelerates as it goes around the sides of the building as corner streams.

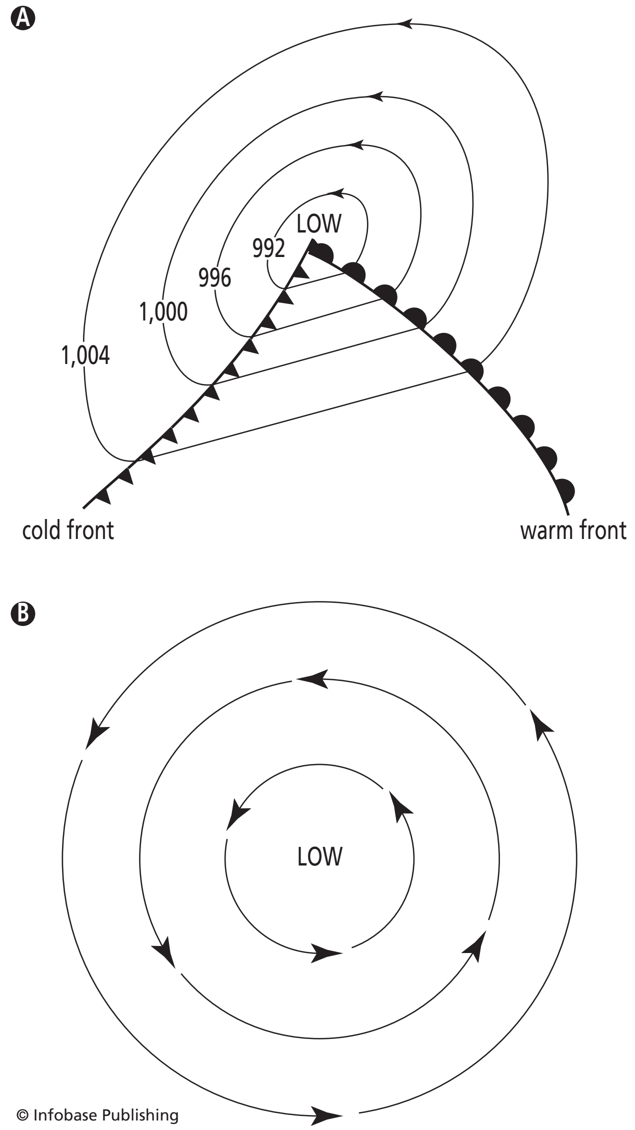
covered the Earth completely in ice (*see* SNOWBALL EARTH).

cryosphere Snow and ice that lie on the surface of the continents and oceans. The perennial cryosphere is confined mainly to polar regions, where it covers 8 percent of the surface of the Earth. In addition, there is a seasonal cryosphere that covers 15 percent of the surface in January (Northern Hemisphere winter) and 9 percent in July (Southern Hemisphere winter). The ice cover is not complete over the Arctic Ocean, but consists of large ice floes that move in relation to one another. The area covered by sea ice varies considerably from year to year. In 1968, the sea was covered with ice between Iceland and Greenland, and in summer 2000 an area at the North Pole was largely free from ice. By 2005, it was evident that arctic sea ice had thinned substantially in recent years and that it was forming later and melting earlier than it had done throughout most of the 20th century.

current A flow of fluid (gas or liquid) that moves through a mass of a similar fluid which remains stationary. Wind is a current of air that moves horizontally through the surrounding air (if all the air were to move it would leave behind a vacuum!). Air currents can be vertical as well as horizontal. Cumuliform clouds (*see* CLOUD TYPES) are produced by vertical air currents caused by CONVECTION. Ocean currents are streams of water that move through the ocean. Many form GYRES. *See* APPENDIX VI: OCEAN CURRENTS.

cyclone (depression) An area of low atmospheric pressure around which there is a clearly defined wind pattern, with the winds flowing cyclonically. Sometimes a cyclone, known as a primary cyclone or primary low, has one or more smaller secondary cyclones within its circulation. A cyclone that is warmer at its center than it is near the edges is called a warm low, warm-core cyclone, warm cyclone, or warm-core low.

A cyclonic circulation is one in which a fluid (liquid or gas) flows in the same direction as that of the Earth's rotation, as this might be seen from directly above the North and South Poles. A cyclonic circulation moves counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Air also flows cyclonically around a TROUGH. At a height of 33 feet (10 m), which is the standard height for observing surface winds, the winds cross the isobars (*see* ISO-) at an angle of 10° to 30°, depending on local topography and the wind speed. Above the PLANETARY BOUNDARY LAYER the winds flow almost parallel to the



(Top) **A cyclone is an area of low pressure. In this case, the cyclone has formed at the boundary between two air masses, at the point where a cold front is advancing toward a warm front. The entire system is traveling to the right. The thin lines are isobars, labeled in millibars with the pressure they indicate. *(Bottom)* Well clear of the surface, the winds flow almost parallel to the isobars, around the center of low pressure. Cyclonic flow is counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.**

isobars at speeds which are proportional to the PRESSURE GRADIENT.

In middle latitudes, cyclones develop in association with the FRONTS between AIR MASSES. They last for only a limited time, forming and finally dying away as the low pressure fills. Often they occur in groups known as cyclone families, with one following another.

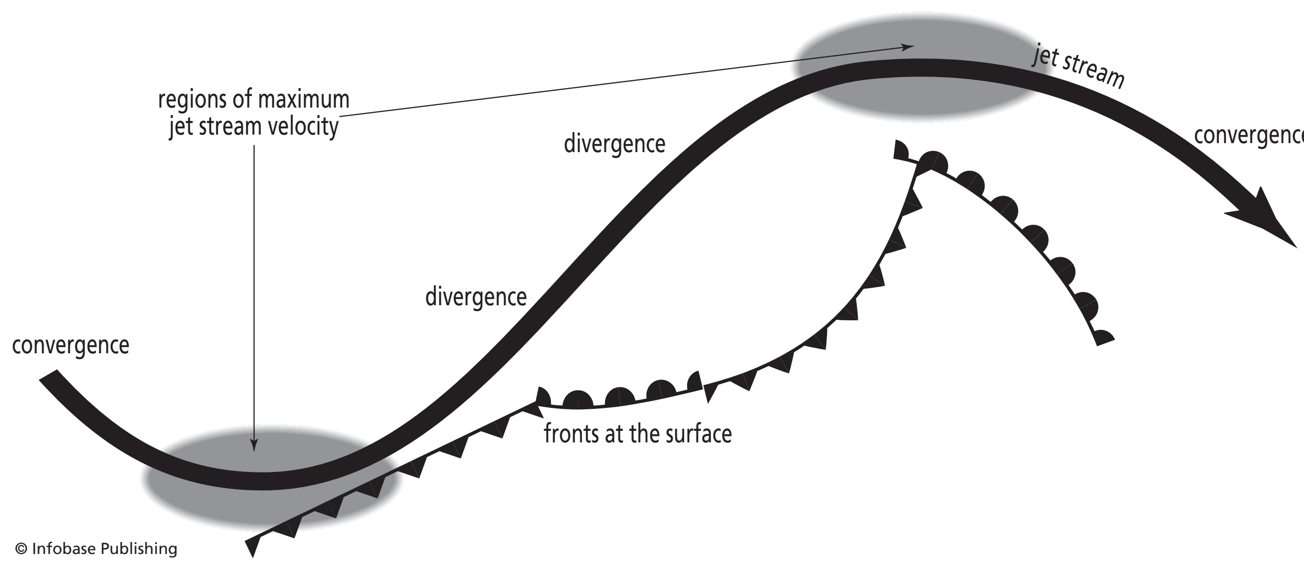
The series of events by which a cyclone develops along the polar front is known as cyclogenesis. The wave theory of cyclones explains cyclogenesis as the formation of waves along the interface (or fronts) between two fluids. When the polar front theory (*see* FRONT) was first proposed, meteorologists had access only to data obtained from air near the surface. With modern access to more complete data, cyclogenesis now takes account of conditions throughout the troposphere and lower stratosphere (*see* ATMOSPHERIC STRUCTURE) and in particular of the JET STREAM and the index cycle (*see* ZONAL INDEX). These exert a strong influence on the formation of weather systems by imposing regions of high-level divergence that remove air faster than low-level convergence (*see* STREAMLINE) can replace it, thus producing an area of low pressure near the surface.

Cyclolysis describes the weakening and disappearance of the cyclonic circulation of air that occurs as a cyclone family dissipates and high pressure comes to dominate. Secondary cyclogenesis is the development of a second cyclone as the first cyclone becomes occluded (*see* OCCLUSION) and starts filling. The new cyclone develops where air is flowing outward in the upper troposphere.

Deepening is a term describing the fall in AIR PRESSURE that occurs at the center of a cyclone. Katabaric (or katallobaric) is the adjective applied to any phenomenon associated with a fall in atmospheric pressure. The place where the air pressure has fallen farther than it has anywhere else over a specified period is known as the pressure-fall center, also called the isallobaric low or katabaric center. The area of lowest surface atmospheric pressure in a cyclone is known as the storm center, a term that applies to any low-pressure system and not only to a tropical cyclone, where cloud usually clears at the center to form an eye.

An increase in air pressure at the center of a cyclone is called filling. A flow of air that develops in the middle and upper troposphere behind a cyclone comprises a dry airstream. This descends once the cyclone has passed.

Midlatitude cyclones often occur as sequences of three or four, each sequence being known as a cyclone family. The first frontal wave (*see* FRONT) to form is called the primary and those following it are secondaries that develop along the trailing edge of a very extended cold front. Each secondary follows a track a little to the south of the one ahead of it. This is because polar air, to the poleward side of the polar front, pushes far-



Cyclogenesis is the formation of a low-level cyclone, associated with an area of convergence along the path of the jet stream.

ther south at the rear of each wave in the sequence. The sequence ends when the polar air has formed a large wedge extending a long way south of the primary wave and establishing a region of high pressure.

A cyclone that develops very rapidly over the ocean is called a bomb. Its development differs from that of most cyclones. The cold front detaches from the warm front and starts moving at right angles to it. This means that the cold front never catches up with the warm front. The center of the low moves rapidly and the warm front is left behind as a back-bent warm front. When the back-bent warm front completely encircles the warm air behind the cold front there is a pool of warm air lying above the center of the cyclone. This warm air is known as a warm seclusion.

A closed cyclone that has become detached from the prevailing westerly air flow and has moved away from it into a lower latitude is known as a cutoff low. A cutoff low can cause BLOCKING.

A cyclone that develops on the LEE side of a mountain and draws air down the mountainside, creating a FÖHN WIND is called a föhn cyclone.

The word cyclone is also used as the local name for a TROPICAL CYCLONE that forms in the Indian Ocean. Cyclones of this type form in both Northern and Southern Hemispheres. Those in the Northern Hemisphere often move northward through the Bay of Bengal and often cause severe damage in India and Bangladesh. Others form farther to the west and move northward into the Arabian Sea, sometimes reaching Oman and Pakistan, or westward to Madagascar. Those in the Southern Hemisphere may reach northern Australia. Cyclones are often extremely severe (*see* APPENDIX II: TROPICAL CYCLONES AND TROPICAL STORMS). Of all the tropical cyclones that develop, 90 percent are either cyclones or typhoons (tropical cyclones that occur in the Pacific).

cyclostrophic wind A strong, low-level wind that follows a very tightly curved path, such as the wind that blows around the side of a hill or around a TORNADO. It is the type of wind that generates a DUST devil when it blows around a very small, but intense, area of low surface pressure.

A cyclostrophic wind occurs when the radius of the path followed by the wind is too small for the CORIOLIS EFFECT to be significant, or close to the equator, where the Coriolis effect is also small—winds around intense TROPICAL CYCLONES are often cyclostrophic. The very strong PRESSURE GRADIENT FORCE exerts a CENTRIPETAL ACCELERATION that balances it, thus maintaining the flow along the curved path parallel to the isobars (*see* ISO-). The equation for calculating the speed (V) of the cyclostrophic wind is:

$$V = \sqrt{(r/\rho)(\delta p/\delta x)}$$

where r is the radius of the curved path, ρ is the air density, and $\delta p/\delta x$ is the pressure gradient.

D

damping A decrease in the amplitude (*see* WAVE CHARACTERISTICS) of an oscillation that occurs over time because resistance to the oscillation drains energy from it. A wind blowing into a forest loses energy by friction with the trees and is slowed. This is a form of damping. Damping mechanisms are built into certain instruments, such as magnetic compasses, to reduce the difficulty of taking a reading from an oscillating needle.

damping depth The depth within which the temperature of soil is affected by DIURNAL or annual temperature changes at the surface. Assuming the soil to be homogeneous throughout the layer, the damping depth (D) is given by:

$$D = (\kappa P/\pi)^{1/2}$$

where κ is the thermal diffusivity (*see* CONDUCTION) of the soil and P is the period (day or year) of the surface temperature change. In addition to mineral particles, soils also contain variable amounts of air and water. These also have thermal diffusivities and damping depths that must be taken into account, depending on the proportion of air and water present in the soil.

The diurnal damping depth for dry sand is 3 inches (7.9 cm), and for wet sand it is 5.5 inches (14 cm). This means that the change in surface temperature as the ground warms in the morning and cools at night is not felt at depths lower than 3 inches in dry sand and 5.5 inches in wet sand. The annual damping depth, below which the yearly cycle of temperature is not felt, is 5 feet (1.5 m) in dry sand and 9 feet (2.7 m) in wet sand.

Dansgaard-Oeschger event (**DO event**) One of the brief warm periods that occurred during the most recent ice age (GLACIAL PERIOD), the Wisconsinian glacial (known in Britain as the Devensian, in northern Europe as the Weichselian, and in the Alps as the Würm). There were many of these events, lasting from hundreds to several thousand years.

At the onset of a DO event the temperature rose in a few decades to a level not much cooler than that of today and when it ended the temperature fell just as abruptly to its ice-age level. The difference between glacial and DO event sea-surface temperatures in the North Pacific amounted to 5.4°F–9°F (3°C–5°C).

DO events appear to be related to HEINRICH EVENTS and to rapid advances and retreats of GLACIERS, suggesting that the events occurred throughout the world. There is also evidence to suggest that DO events may also have occurred during the last INTERGLACIAL, known as the Sangamonian in North America, the Eemian in northern Europe, Riss–Würm in the Alps, and Ipswichian in Britain. During this interglacial average temperatures were similar to those of today.

The existence of DO events was discovered in the early 1980s by the Danish climatologist Willi Dansgaard, the Swiss climatologist Hans Oeschger (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), and the American climatologist Chester C. Langway Jr. from their examination of ICE CORES taken from the GREENLAND ICE SHEET. These findings were later confirmed examining samples taken from the bed of Lake Gerzensee, near Bern.

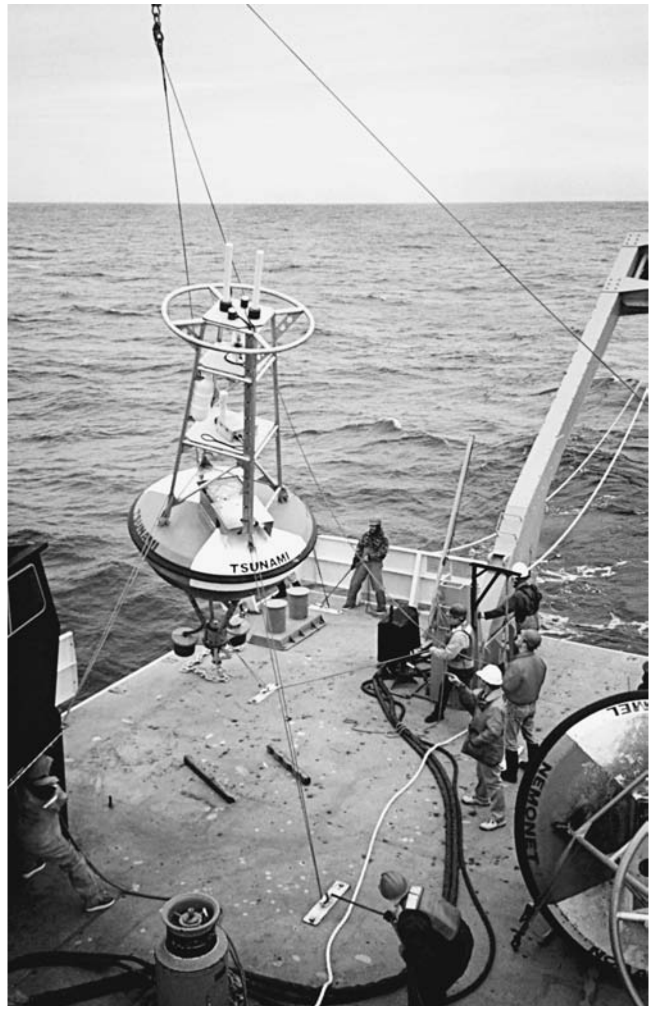
Darcy's law A mathematical equation that expresses the relationships among the various factors that determine the rate at which GROUNDWATER moves through an AQUIFER. The law was proposed by the French engineer Henri-Philibert Gaspard Darcy (1803–58; *See* APPENDIX I: BIOGRAPHICAL ENTRIES) and it states that:

$$Q = kIA$$

where Q is the rate of groundwater flow, k is the PERMEABILITY of the aquifer, I is the gradient of the slope down which the water is moving, and A is the cross-sectional area of the aquifer through which the water is moving.

data buoy An instrument package that is located in a fixed position offshore and transmits continuous measurements of the surface conditions at sea. These include wind speed and direction and sea-surface temperature. Data buoys have been sited along the eastern coast and Gulf coast of the United States since the early 1970s. They supply information that is used in the compilation of daily weather forecasts and they also form an important component of the hurricane warning system.

In the world as a whole there are approximately 1,500 buoys acquiring meteorological data. Argo floats, designed to track the movement of ocean currents, are the latest addition to the fleet of these automated devices. Argo floats sink to a depth of 6,500 feet (2,000 m), taking measurements as they do so. Every 10 days each float surfaces, transmits its stored data to an orbiting satellite, and sinks once more.



Deploying an oceanic buoy from the NOAA ship *Ronald H. Brown.* *(Commander Emily B. Christman, NOAA Ship Collection)*

datum (*pl.* **data**) Something that is known or assumed to be true, a premise from which inferences may be drawn, or the fixed starting point of a scale.

A point or level surface that is used as a base from which other elevations can be measured is called a datum level. The point or surface is therefore a datum. The most widely used datum level is the sea surface. Altitudes in the atmosphere, the elevation of cities, the heights of mountains, and the depth of the sea are all measured against a sea-level datum.

day The time that it takes for the Earth to complete one rotation about its axis. This is usually measured from noon on one day to noon on the following day. In SI units (*see* APPENDIX IX: SI UNITS AND CONVERSIONS) one day is equal to 86,400 seconds. This varies slightly with changes in the rotation of the Earth and so the figure given is the mean calculated over several years.

The length of a day is not the same when measured in respect of the position of the Sun as it is when measured against the position of a fixed star. To distinguish the two, the day measured with reference to a fixed star is known as the sidereal day. A sidereal day is the time it takes for the Earth to complete one revolution on its axis so that a point on the surface returns to the same position in relation to a fixed star. Its mean length is 86,164 seconds, which is 236 seconds shorter than the mean solar day. One solar day is therefore equal to 86,636 seconds of mean sidereal time. A sidereal month is the average time taken by the Moon to complete one orbit of the Earth and return to the same position with reference to the fixed stars. It is 27 days, 7 hours,

Month											
N	S	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
Jan	Jul	12.07	11.35	11.02	10.24	9.37	8.30	6.38	0.00	0.00	0.00
Feb	Aug	12.07	11.49	11.21	11.10	10.42	10.07	9.11	7.20	0.00	0.00
Mar	Sep	12.07	12.04	12.00	11.57	11.53	11.48	11.41	11.28	10.52	0.00
Apr	Oct	12.07	12.21	12.36	12.53	13.14	13.44	14.31	16.06	24.00	24.00
May	Nov	12.07	12.34	13.04	13.38	14.22	15.22	17.04	22.13	24.00	24.00
Jun	Dec	12.07	12.42	13.20	14.04	15.00	16.21	18.49	24.00	24.00	24.00
Jul	Jan	12.07	12.40	13.16	13.56	14.49	15.38	17.31	24.00	24.00	24.00
Aug	Feb	12.07	12.28	12.50	13.16	13.48	14.33	15.46	18.26	24.00	24.00
Sep	Mar	12.07	12.12	12.17	12.23	12.31	12.42	13.00	13.34	15.16	24.00
Oct	Apr	12.07	11.55	11.42	11.28	11.10	10.47	10.11	9.03	5.10	0.00
Nov	May	12.07	11.40	11.12	10.40	10.01	9.06	7.37	3.06	0.00	0.00
Dec	Jun	12.07	11.32	10.56	10.14	9.20	8.05	5.54	0.00	0.00	0.00

(The time of sunrise and sunset during the current year for any location in the world can be obtained from the Astronomical Applications Department of the U.S. Naval Observatory at aa.usno.navy.mil/AA/data/docs/RS_OneYear.html and also from the Custom Sunrise Sunset Calendar at www.sunrisesunset.com/custom_srss_calendar.asp)

and 43 minutes. A sidereal year is the time it takes the Earth to complete one orbit of the Sun; its mean value is 365.256 sidereal days.

The word *day* is also used to mean the length of daylight. In this sense day is contrasted with night. Hours of daylight are measured from the first appearance of the rim of the Sun above the eastern horizon to the disappearance of the upper rim of the Sun on the western horizon.

Daylength varies according to the latitude and SEASON. Summer days are long and winter days are short, but the extent to which they are so differs greatly from place to place. At the March and September EQUINOXES the Sun is directly overhead at noon at the equator, and on those two days there are 12 hours of daylight and 12 hours of darkness throughout the world. At the June and December SOLSTICES the Sun is directly overhead at noon at the tropics of Cancer and Capricorn respectively (*see* TROPICS). On those two days the difference in length between day and night is at its maximum.

Because the relative lengths of day and night are determined astronomically, they can be predicted with great accuracy for any place on Earth on any day of the year. Inside the Arctic Circle and Antarctic Circle (*see* AXIAL TILT), the longest day of the year lasts a full 24 hours (86,400 sec), and the shortest day of the year has no length at all, because the rim of the Sun does not appear above the horizon. At the equator, daylight on every day in the years lasts for 12 hours 7 minutes (43,620 s). At New York City (40.72°N) the longest day of the year lasts for 15 hours 6 minutes and the shortest for 9 hours 15 minutes. At Los Angeles (34.05°N) the longest day lasts for 14 hours 26 minutes and the shortest for 9 hours 53 minutes.

The table above shows the hours of daylight on the 15th of each month in hours and minutes for different latitudes. The months are listed twice, for the Northern (N) and Southern (S) Hemispheres.

DDT (*pp'***dichlorodiphenyltrichloroethane**) An insecticide that came into widespread use in the 1940s, first to control insect vectors of human diseases and later to control agricultural pests. Restrictions were imposed on its use in most countries starting in the late 1960s because, although it posed very little danger to human health, traces of it accumulated along food chains and caused harm to wildlife, especially to birds of prey.

DDT evaporates from the soil and also adheres to dust particles. Its HALF-LIFE of about three years allowed time for airborne DDT to become distributed throughout the world at very low concentrations. In the 1960s, it was detected in air by means of the ELECTRON CAPTURE DETECTOR invented by James Lovelock (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), and it was this discovery that gave rise to campaigns to have it banned. These campaigns marked the emergence of the environmentalist movement.

DDT was first synthesized in 1873 by an Austrian chemist, Othmar Zeidler. Later it was synthesized again by Swiss chemist Paul Hermann Müller (1899–1965). Müller recognized its insecticidal properties, and in 1943 the compound was patented in Switzerland and Britain. For this achievement Müller was awarded the 1948 Nobel Prize in chemistry.

Defense Meteorological Satellite Program (DMSP) A program that is run by the Air Force Space and Missile Systems Center to collect meteorological and oceanographic data and to monitor the space environment through which Earth moves. The program involves the design, building, launching, and maintenance of a number of satellites. These are in near Sun-synchronous ORBITS, with an orbital period of about 101 minutes. These orbits carry the satellites close to the poles at a height of about 516 miles (830 km). They cross every point on the Earth up to twice every day.

Instruments carried on the satellites monitor a swath 1,860 miles (3,000 km) wide, recording images in visible and infrared light (*see* SOLAR SPECTRUM). Their scanning radiometers (*see* SATELLITE INSTRUMENTS) gather information that is used to determine cloud height and type, land and water surface temperatures, ocean currents, and ice and snow. The data are transmitted to ground-based terminals and eventually used in planning U.S. military operations and in compiling civilian weather forecasts. Every day, data is also sent to the Solar Terrestrial Physics Division of the National Geophysical Data Center, where it is added to an accumulating archive.

Further Reading

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deforestation The permanent removal, by clear-felling, of an area of forest. On steep slopes, the removal of tree cover can leave the ground unprotected from heavy rain and RUNOFF. This can lead to serious EROSION.

Deforestation can also cause local climatic changes, principally by altering the movement of water. TRANSPIRATION is reduced and WIND SPEED increases as the sheltering effect of the trees is lost. Together, the effect is to lower the HUMIDITY of the air. This reduces both PRECIPITATION and EVAPORATION.

A change from dark-colored trees to paler grasses or crops also increases the surface ALBEDO. This offsets the increased intensity of sunlight once the shading effect of the trees is lost and, combined with the increased wind, this means that the surface temperature changes little. There is no evidence that deforestation can have a large direct effect on climates far from the region in which it occurs, but it may have an indirect one. As the root systems of the forest decompose the carbon they contain is oxidized to carbon dioxide, most of which escapes into the air. Consequently, it is possible that widespread deforestation may be followed some time later by a major release of CO_2.

degree-days The number of degrees by which the mean daily temperature is above the minimum temperature needed for growth—called the zero temperature—for a particular crop plant. This indicates the time it will take for a crop plant to mature. The zero temperature for corn (maize), for example, is about 55°F (12.8°C), and in northern Utah corn needs 1,900–2,600 degree-days. The sum of all the individual degree-days is called the total degree-days.

Heating degree-days are a version of degree-days used by heating engineers in their calculations of fuel consumption. One heating degree-day is equal to one degree by which the mean daily temperature falls below a base level. In the United States the base level is 65°F or 19°C. The sum of the heating degree-days over a month, season, or year indicates the amount of heating that will be needed. The calculation is based on the duration and intensity of solar radiation, however, and takes no account of cooling by radiation, evaporation, or wind.

The cumulative number of degree-days when the air temperature is below freezing (32°F, 0°C) is known as the freezing index and the cumulative number of degree-days when the air temperature is above freezing (32°F, 0°C) is known as the thawing index. Freezing and thawing indices are used to predict the distribution of PERMAFROST, to estimate the thickness of ice on lakes, rivers, and the sea, to estimate the depth to which frost penetrates below ground, and to classify types of SNOW. The indices are available for the entire world, broken into areas measuring 0.5° longitude by 0.5° latitude.

The time that elapses between the lowest point and the succeeding highest point on the time curve of cumulative degree-days when the air temperature is above and below freezing (32°F, 0°C) defines the thawing season.

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dehumidifier A device that is used to reduce the HUMIDITY of air that is too moist for comfort. Dehumidifiers are incorporated in many air-conditioning systems, especially those used in large buildings.

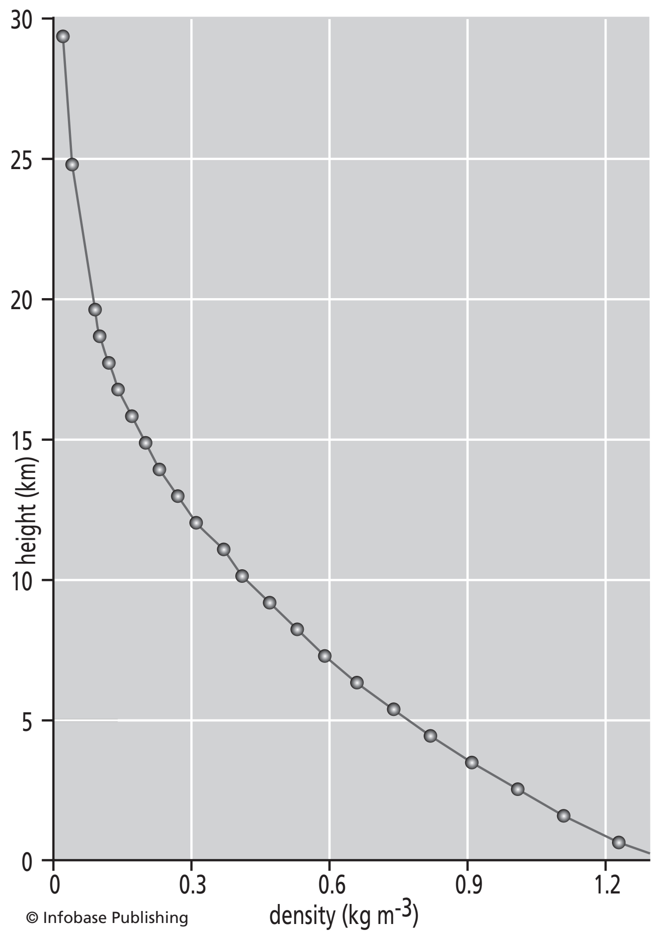
There are two ways air can be dried. It can be passed through a spray of very cold water. This chills the air to below its dew point temperature (*see* DEW), causing water vapor to condense. Alternatively, the air can be passed across a bed of crystals of a hygroscopic substance such as common salt. The crystals absorb water directly from the air.

It is also possible for air to be too dry for comfort. In this case a device called a humidifer (*see* HUMIDIFICATION) is used to add moisture.

density The mass of a unit volume of a substance. It is measured in pounds per cubic foot (lb/ft^3) or pounds per cubic inch (lb/in^3), and in SI units (*see* APPENDIX IX: SI UNITS AND CONVERSIONS) in kilograms per cubic meter (kg/m^3). Under a standard atmosphere (*see* UNITS OF MEASUREMENT), pure water has a density of 0.6 pounds per cubic foot (0.036 lb/in^3, 1,000 kg/m^3).

The density of a fluid varies with temperature. As the temperature decreases, atoms or molecules of the fluid move closer together. Consequently, the volume of a body of fluid decreases and its density increases, because the same number of atoms or molecules is packed into a smaller volume. The opposite occurs as the temperature rises. Air temperature decreases with altitude and, therefore, the density of air varies with altitude. Under an international standard atmosphere the density of air is 0.08 pound per cubic foot (1.23 kg/m^3), assuming a relative HUMIDITY of 50 percent and a carbon dioxide content of 0.04 percent by volume. If this were the density of the air throughout the whole of the atmosphere, the thickness of the atmosphere would be 5.2 miles (8.4 km). This is called the scale height. In fact, the air density at that height (27,500 feet; 5,200 m) is 0.03 pound per cubic foot (0.5 kg/m^3). At a height of 18.6 miles (30 km) the air density is 0.001 pound per cubic foot (0.02 kg/m^3), which is about 1.6 percent of its mean sea-level density.

The ratio of the density of air at a specified altitude to the density of air at the same altitude in a standard atmosphere is called the density ratio. A homogeneous



The decrease in air density with altitude

atmosphere is a hypothetical atmosphere in which the density of the air remains constant at all heights. An isosteric surface is one across which the density of the air remains constant.

A difference in density between two adjacent bodies of air may cause air to flow from one body to the other. This moving air is called a density current. Density currents occur when cold air undercuts warmer air at a cold FRONT. KATABATIC WINDS, such as mountain breezes, are also density currents. A mountain breeze occurs when air high on a mountainside is chilled by contact with a snow-covered surface. The density of the air increases as its temperature falls and the air begins to move down the slope, displacing the warmer, less dense air at a lower level.

The height above the surface at which the density of the air has a specified value is known as the density altitude. For an airplane flying at a known airspeed, air density determines the amount of lift its wing and tailplane surfaces will produce, the amount of drag it will experience, and the power that its engines will yield. An instrument in the cockpit shows the density of the outside air. By finding this figure in a table that shows the temperature, pressure, and density of air at various altitudes in a standard atmosphere, the pilot can read the density altitude. This is the altitude at which air has the measured density in a standard atmosphere, regardless of the actual height of the airplane above the surface. When approaching an airfield after a long flight, the pilot needs to know the density altitude of the runway in order to calculate the way the airplane will respond to its controls.

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denudation The stripping away of the material that covers the surface of the land, leaving bare rock exposed. The word is derived from the Latin verb *de nudare,* which means "to strip completely naked." Denudation includes the processes of WEATHERING, EROSION, and the transport of material that has been detached from the surface.

deposition The formation of ice on a solid surface by the direct conversion of water vapor into ice without passing through the liquid PHASE. This is the mechanism by which hoar FROST forms. Sometimes the term SUBLIMATION is used to describe both the freezing of water vapor and the direct vaporization of ice. Nowadays it is more usual, however, to describe ice formation as deposition, reserving sublimation for the conversion of ice to water vapor.

Water vapor will also freeze directly to form ICE CRYSTALS. In order to do so, however, solid particles must be present on which the ice can form. Such particles are called sublimation nuclei. Sublimation nuclei trigger the formation of ice crystals by direct deposition from air that is adjacent to supercooled (*see* SUPERCOOLING) droplets. The ice crystals then act as FREEZING NUCLEI and the proportion of ice particles in that part of the cloud increases at the expense of supercooled water.

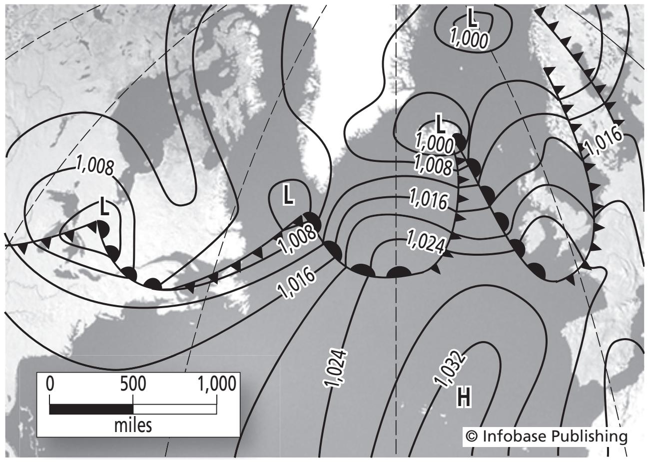
depression The name that is commonly used to describe a midlatitude frontal CYCLONE (*see* FRONTOGENESIS). The term depression refers to a well-defined area of low atmospheric pressure; it is the AIR PRESSURE that is depressed. Cyclone refers to the circulation of air around the low-pressure center; this is cyclonic.

The two words both describe the same phenomenon, but from different points of view. Depression is used informally rather than cyclone, because cyclone is popularly associated with TROPICAL CYCLONES. Mention of an approaching cyclone in a TV weather forecast might distress viewers, when all they need fear is a period of rain or snow.

A depression that occurs in middle latitudes (outside the TROPICS) and around which the air circulates cyclonically is also known as an extratropical cyclone. It is a cyclone, because air circulates it cyclonically, but the process causing it is quite different from that which causes a tropical cyclone.

The arrival of air from a lower latitude on the eastern side of a cyclone or on the western side of an ANTICYCLONE (in the Northern Hemisphere) sometimes brings a warm wave. This is a sudden rise in temperature that occurs in middle latitudes, usually in summer. In either case the warm wave often heralds wet weather from an approaching depression.

A depression that forms around the point where a cold FRONT and warm front meet and warm air is



A family of wave depressions seen as they are crossing the North Atlantic

beginning to rise over, or be undercut by, the cold air, is sometimes called a wave depression or wave cyclone. The frontal system is shaped like a wave on a synoptic chart (*see* weather map), with a center of low pressure and cyclonic circulation at the peak of the wave. Wave depressions are a feature of weather systems in middle latitudes. They move from west to east, carried by the prevailing westerlies (*see* wind systems), and several often occur one after the other. These comprise a depression family, and each member of the family is linked to a wave in the jet stream above it (*see* zonal index). Depression families bring prolonged periods with gray skies and wet weather, interrupted only briefly by the ridges between one depression and the next.

A depression that consists of cold air surrounded by warmer air at a higher pressure is called a cold low or cold pool. Cold lows often form in winter in the middle troposphere (*see* atmospheric structure) over northeastern North America and northeastern Siberia, and they are usually persistent. They probably result from strong vertical movement and associated adiabatic (*see* adiabat) cooling in occlusions along the coast. Surface pressure may be high or low beneath the low. Cold lows produce extensive middle and high cloud (*see* cloud classification) that reduces the rate at which the ground cools by radiation. They also form in lower latitudes when pools of polar air (*see* air mass) are isolated during the latter stages of the index cycle (*see* zonal index). This type of cold low produces cumuliform cloud with showers and thunderstorms in summer.

A Genoa-type depression is common in winter over the western Mediterranean, following a sudden drop in pressure that occurs around October 20 when the Azores high collapses. The sea-surface temperature in the Mediterranean is then about 3.6°F (2°C) higher than the mean air temperature, and when colder air crosses the sea it quickly becomes unstable. A Genoa-type depression develops over the Gulf of Genoa, in the lee of the Alps and Pyrenees Mountains, in maritime polar air. Because the air in the warm sector (*see* front) is very unstable, the depression produces very intense precipitation along the warm front and heavy showers and thunderstorms to the rear of the cold front, often with cumuliform clouds extending to a height of more than 20,000 feet (6,000 m). About 74 percent of winter depressions in the western Mediterranean are of this type. About 9 percent are depressions that form over the Atlantic and about 17 percent are Saharan depressions.

Saharan depressions form in winter over the western Mediterranean. They develop in the lee of the Atlas Mountains when cold, maritime polar air crosses the warmer sea surface and becomes unstable. Saharan depressions are the most important source of rainfall in this region in late winter and early spring.

Not all depressions are associated with a frontal system. Most tropical depressions are nonfrontal depressions, caused either by differential heating of the surface or by disturbances such as easterly waves (*see* tropical cyclone).

A tropical depression is a type of nonfrontal depression that develops in the Tropics through the convergence of air (*see* streamline) at low level. Convergence causes the air to rise, producing low pressure at the surface. Winds around the depression blow at less than 38 MPH (61 km/h). If the depression deepens and these speeds increase, however, the depression is reclassified as a tropical storm.

A polar-air depression is a type of nonfrontal depression that occurs only in the Northern Hemisphere. It forms when unstable arctic or polar maritime air moves southward along the eastern side of a large ridge extending along a north–south line.

The path that depressions usually follow as they cross the United States from west to east during the summer is called the northern circuit. The path takes them across the Great Lakes and St. Lawrence River. Although depressions follow the circuit most often in summer, the depressions themselves are weaker then than they are at other times of year. In winter they usually follow the southern circuit, a path sometimes carries them as far south as the Gulf of Mexico.

desert A desert is a region where the potential EVAPORATION is greater than the average annual PRECIPITATION. Potential evaporation is the amount of water that would evaporate from the surface were there an unlimited supply of water. If this exceeds the amount of precipitation, precipitation will evaporate very quickly and the ground will remain permanently dry. Desert conditions will inevitably result.

Potential evaporation varies with the temperature, because the rate of evaporation is greater at high temperatures than it is when the temperature is low. Consequently, in order for a desert to develop, the average precipitation must be much lower in a high latitude than would be needed in a low latitude. Regardless of average temperatures, however, a desert is likely to form wherever the average annual precipitation is less than 10 inches (254 mm).

There are several types of desert that form under different conditions. A coastal desert is one found close to a coast and often running parallel to it. The desert of Baja California, Atacama Desert in Chile, Namib Desert in Namibia, and parts of the Sahara along the western coast of North Africa, are coastal deserts.

Two factors are principally responsible for the development of a coastal desert. Where the desert is in the TROPICS and on the western side of a continent, air reaching it is carried by the trade winds (*see* WIND SYSTEMS) blowing from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. The air must cross an entire continent and its mountains, losing moisture as it does so. The air is very dry by the time the air reaches the coastal strip.

Air that approaches such deserts from the ocean crosses a cold eastern BOUNDARY CURRENT that flows parallel to the coast with UPWELLINGS that bring cold water to the surface. The lowest layer of approaching air is cooled by contact with the cold water. This increases its stability (*see* STABILITY OF AIR), producing a shallow INVERSION, and often chills it to below its dew point temperature (*see* DEW). The effect is to lower the air temperature over the land and reduce the annual temperature range. It also produces frequent FOG and low cloud. Although the air is moist, however, and the relative HUMIDITY often reaches 90 percent, the clouds rarely produce rain, because the inversion inhibits CONVECTION. These are the driest of all subtropical deserts. At Iquique, Chile, for example, the average relative humidity is 81 percent, but the average annual rainfall is 1.1 inches (28 mm). Over one five-year period it did not rain at all at Iquique during the first four years, but in July of the fifth year there was a shower that delivered 0.6 inch (15.24 mm) of rain. There are parts of the Atacama Desert where no rain has ever been recorded, and there are riverbeds that have remained dry for the last 120,000 years. This region has been extremely arid for at least the last 20 million years.

A cold desert develops outside the Tropics in the interior of a continent. Its great distance from the ocean ensures that the air reaching it is very dry. The Gobi and Takla Makan deserts of Asia are of this type.

An ice desert is an area that is permanently covered with ice or snow and which supports no vegetation of any kind, other than single-celled algae that arrive attached to snowflakes. Deserts of this type form over the surface of ICE SHEETS when these extend into lower latitudes during GLACIAL PERIODS.

A polar desert is an area inside the Arctic or Antarctic Circle (*see* AXIAL TILT) where the annual precipitation is very low, although most of the surface is covered with snow and ice. The low precipitation is due mainly to two factors. First, the air is subsiding and diverging at the surface (*see* GENERAL CIRCULATION). This air previously ascended to the height of the tropopause (*see* ATMOSPHERIC STRUCTURE) along the polar FRONT. As it rose, its temperature fell and it lost most of its moisture, so by the time it subsides again it is very dry. Its low-level divergence (*see* STREAMLINE) prevents moister air from entering. The second factor is the low air temperature over the Arctic and Antarctic regions, which means the air is able to hold very little moisture.

Subtropical deserts lie approximately between latitudes 20° and 40° in both hemispheres and are found in all the continents. Examples include the Sonoran desert of the United States and Mexico, the Sahara, the Syrian desert, and the deserts of the Near East, Middle East, and Australia.

These deserts are caused by the SUBSIDENCE of air on the descending sides of the Hadley cells (*see* GENERAL CIRCULATION). Air in the Hadley cells rises by convection and loses its moisture as it ascends and cools adiabatically (*see* ADIABAT). It descends again as very dry air that warms adiabatically during its descent. It reaches the surface as hot, dry air, and its subsidence produces high surface pressure and an outward flow of air. The outward flow prevents moister air from entering the high-pressure region. Consequently, the climate is extremely arid.

Subtropical deserts tend to occupy the western sides of the continents, although the Sahara extends across the whole of Africa. This is because the flow of air is anticyclonic around the SUBTROPICAL HIGHS, and the centers of these ANTICYCLONES are over the eastern sides of the oceans. The anticyclonic flow brings cool, dense air toward the equator on the western sides of the continents, intensifying the subsidence and high pressure there.

A tropical desert is the part of a subtropical desert that lies within the Tropics, closer to the equator than latitude 23.5°N or S.

The Sabria oasis, southern Tunisia, in the Sahara Desert, as it appeared in about 1965. ***(Keystone/Getty Images)***

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desertification The deterioration of land until it has the characteristics of a dry desert. The fact that this happens leads to the supposition that some or all deserts may be expanding as they encroach onto adjacent land.

Modern fears of this process began in the early 1970s. Prolonged DROUGHT in the SAHEL region of Africa forced people to migrate and led to the deaths of more than 100,000 people and the loss of up to 4 million livestock. In 1973, drought in Ethiopia is believed to have claimed up to 250,000 lives and the drought returned in 1984–5.

Aerial and satellite photographs taken at the time revealed that the vegetation was being damaged over large areas where farm livestock was being allowed to graze with no control. The pictures also showed fenced areas where grazing was controlled and the vegetation was in much better condition. This led some people to conclude that human behavior was responsible for the spread of the desert.

The United Nations held a Conference on Desertification in Nairobi in 1977. Officials of the United Nations claimed to have coined the term *desertification* to describe the process, but the word was first used, in French, in 1949, in *Climats, Fôrets et Desertification de l'Afrique Tropicale* (Climates, Forests and Desertification of Tropical Africa) by A. Aubreville. In fact, fears of the southward advance of the Sahara were being expressed in the 1930s. That was also the decade during which prolonged drought in North America produced the DUST BOWL, with attendant fears of desert expansion. The United Nations Environment Programme defines desertification as "land degradation in arid, semi-arid, and dry sub-humid areas resulting mainly from adverse human impacts." Scientists now dispute that land degradation results mainly from poor human land management.

The problem is not confined to Africa. Approximately 47 percent of the total land area of the world, amounting to 20 million square miles (52 million km^2), has a dry climate, of which 60–70 percent has suffered some degree of desertification. Africa and Asia have been most seriously affected, each of these continents having

32 percent of the total degraded land. North America has 12 percent, Australia 11 percent, and South America 9 percent. An estimated 7.7 million square miles (20 million km^2) is thought to be vulnerable to degradation. Of that total, 29.7 percent is at present agricultural land, 34.8 percent is permanent grassland, and 35.5 is woodland and forest.

It is uncertain whether the deserts as a whole are spreading. The idea that they are advancing rapidly is certainly incorrect, and satellite data suggest that the area of the Sahara did not change between 1980 and 1997 and may have changed very little since the 19th century, although the southern edge of the desert fluctuates.

Scientists now believe that droughts in the semiarid lands bordering deserts are entirely natural phenomena in which human activity plays no part. They occur at irregular intervals, sometimes last for several years, and then end with the return of the rains. Both the Sahel and Ethiopia recovered from the droughts that devastated them.

During the drought, however, land management becomes critically important. As the pasture dries, semi-nomadic peoples whose livelihoods depend on their cattle, sheep, goats, and camels, are likely to be crowded into the areas where the pasture survives. This may lead to overexploitation of the vegetation. Similarly, where once nomadic peoples are encouraged to settle in permanent villages, taking their livestock with them, the pasture around the village is often destroyed. Trees and shrubs are also removed, for use as fuel.

In this situation, desert soils dry to DUST and, blown by the wind, they bury the plants on land nearby. Dust coats plant leaves, inhibiting PHOTOSYNTHESIS, and more vegetation dies. Most scientists now agree that this deterioration can be described as desertification only if it affects vegetation as well as the soil, if it is caused partly by human activity, and if the deterioration continues for at least 10 years. If rain returns, all or most of the affected land can be made to recover.

Desertification was debated at the Rio Summit (the United Nations Conference on Environment and Development) held in June 1992 in Rio de Janeiro, where it was agreed that a treaty should be prepared as a guide to nations in halting land degradation. This led to the United Nations Convention to Combat Desertification (CCD). This is based on local schemes that are coordinated internationally.

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determinism The idea that comprehensible natural laws govern the transition of a system from its present to a future state. In other words, laws acting upon the present condition determine the future condition. It follows that if it were possible to know the present condition in sufficient detail and to understand the laws completely, the entire future could be predicted. The weather, for example, could be forecast accurately for years or even centuries in advance. If the weather system is deterministic, it means its state results entirely from forcing (*see* CLIMATIC FORCING). If a system is not deterministic, it may be STOCHASTIC or chaotic (*see* CHAOS).

detrainment An outflow from a body of moving air into the surrounding air. The process occurs when a cumuliform cloud (*see* CLOUD TYPES) dissipates. Its CLOUD DROPLETS evaporate, the smallest ones first. The cloud grows darker in color, because the larger droplets scatter less light than the small ones. Finally all the droplets have gone and the water vapor and air with which it is mixed disperse into the surrounding air. Detrainment from the top of a towering cumulonimbus cloud can release water vapor that forms cirrostratus at a higher level.

Devonian The earliest period of the Upper Palaeozoic sub-era, which began 416 million years ago and ended 359.2 million years ago. The Devonian, named for the area in Devon, England, where rocks of this age were first identified, is divided into three epochs: Early (began 416 million years ago); Middle (began 397.5 million years ago); and Late (began 385.3 million years ago).

During the Devonian, the southern supercontinent of Gondwana was moving steadily northward and in the Northern Hemisphere the continents of Laurasia and Baltica collided, closing the Iapetus Ocean and raising a mountain chain in what is known as the Caledonian orogeny.

Tropical weather conditions occurred in a narrow belt on either side of the equator, with arid zones extending to about 35° in both hemispheres. Climates were temperate from about latitude 35° almost all the way to the North and South Poles. In the Late Devonian, temperatures fell in the Southern Hemisphere, and GLACIERS may have formed in parts of western Gondwana (modern northern South America). At the same time in the Northern Hemisphere, the subtropical belt extended almost to 60°N.

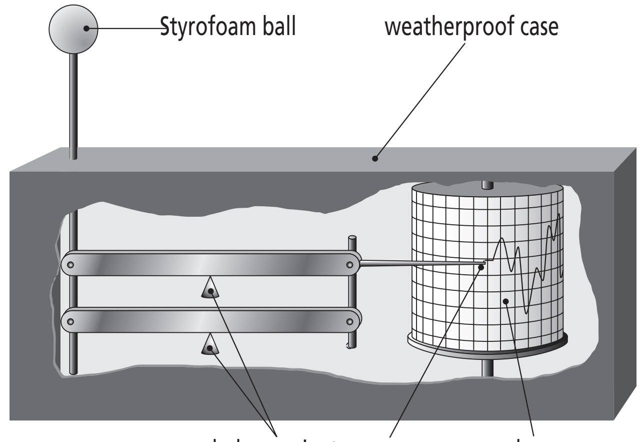
dew Moisture that condenses from the air onto the surface, most commonly onto plant leaves. It forms during cool nights when there is little wind. Heat that the ground absorbed during the day is radiated away from the ground surface. This produces a layer of cool air adjacent to the surface. If the air is chilled sufficiently for its relative HUMIDITY to exceed 100 percent, water will condense onto surfaces. This is dew.

If the air is completely still, the water that has condensed cannot be replaced from the moister air above, so only a small amount of dew will form. A slight movement of the air will bring moister air to a low level, where some of its water vapor condenses to add to the accumulation of dew. If the wind is too strong, however, warmer air will replace the cool surface air and condensation will not occur. The wind speed at which dew forms varies according to the roughness of the surface.

Dew will also form when warm air comes into contact with a surface at a lower temperature. This process is called contact cooling. It can reduce the temperature of the lower air to below the dew point temperature. Depending on the amount of moisture present and the thickness of the layer of air that is cooled, CONDENSATION will produce dew or FOG.

The dew point temperature is the temperature at which a PARCEL OF AIR would become saturated if it were cooled with no change in the amount of moisture it contained or in the atmospheric pressure. As the air is chilled to below its dew point temperature, water condenses onto surfaces as dew. The dew point temperature can be read from a table in which it is calculated from the dry-bulb TEMPERATURE and wet-bulb depression (*see* THERMOMETER) measured by a psychrometer (*see* PSYCHROMETRY). Alternatively, it can be read directly from a dew cell (*see* HYGROMETER).

If the air is chilled to below freezing, it passes the frost point and hoar FROST will form. Dew that freezes after it has formed is called white dew. It is more opaque, and therefore whiter, than hoar frost.



A dew gauge measures the formation of dew. The weight of moisture that condenses as dew onto the plastic (Styrofoam) ball is weighed by a system of balances and a pen records the changing weight on a rotating drum.

The difference between the ambient temperature and the dew point temperature is known as the dew point depression. This is approximately double the wet-bulb depression. Dew point depression is one of the ways in which meteorologists specify the amount of water vapor present in the air. For example, at an ambient temperature of 68°F (20°C) and a relative humidity of 75 percent, the dewpoint depression is 7.9°F (4.4°C) and the wet-bulb depression is 15.7°F (8.7°C).

The amount of dew is measured using an instrument called a dew gauge or surface wetness gauge. This device comprises a Styrofoam ball of a standard size. The weight of the ball changes as dew condenses onto it and the instrument records this change in weight. The ball is held at the end of a vertical arm that is connected to a system of balances. A pen at the end of one of the balance arms makes a continuous record on a chart fixed to a rotating drum. The Styrofoam ball is exposed, but the remainder of the device is enclosed by a weatherproof case. Siting of the gauge is important. If it is to give a true reading for only condensation it must be protected from rain and from water dripping from foliage.

Farmers in some parts of the world have traditionally collected dew to provide water for livestock in a dew pond. They excavated a shallow pond and lined it with compacted clay. Dew collected in the bottom of the pond, hence the name. Most of the water arrived as rain, however.

diabatic temperature change A change in the temperature of air that is due to contact with the surroundings; the change is not adiabatic (*see* ADIABAT).

Diabatic temperature changes occur in the layer of air adjacent to the surface of the Earth. This air is in contact with the surface, by which it is warmed or cooled, and the horizontal movement of air is strongly affected by the roughness of the surface (*see* AERODYNAMIC ROUGHNESS). The surface roughness produces EDDIES that have the effect of mixing the air thoroughly.

diapause A temporary cessation of growth and development that an insect enters during a period of adverse conditions, usually cold or dry seasonal weather. Development resumes as soon as conditions improve. Insects can enter diapause as eggs, larvae, pupae, or as adults.

differential heating The warming of surfaces at varying rates when they are all equally exposed to sunshine. Surface heat at different rates for a number of reasons. A dark surface warms faster than a pale surface, because its ALBEDO is lower. Sand warms faster than peat, because it has a higher thermal conductivity (*see* CONDUCTION) and a lower HEAT CAPACITY. Wet material warms more slowly than dry material, because of the high heat capacity of water and also because wet surfaces are cooled by EVAPORATION.

Differential heating causes ANABATIC WINDS and LAND AND SEA BREEZES, and in hot, dry climates it produces DUST devils and desert WHIRLWINDS.

diffraction The bending of light as it passes close to the sharply defined edge of an object by an amount that is proportional to the wavelength of the light (red light is diffracted more than blue light because its wavelength is greater). This causes the edge to appear blurred, but it also gives rise to INTERFERENCE, as different parts of the spectrum meet. This produces certain OPTICAL PHENOMENA.

diffusion Mixing that occurs when one fluid is added to another, but the two are not stirred or otherwise agitated. Diffusion is due to the random movement of molecules. Molecules of one component mingle with those of the other until the two types of molecule are distributed evenly throughout the fluid, which is then called a *mixture*. This process can be seen, for example, when a few drops of a food dye are added to clean water. Almost at once, the color begins to spread outward and eventually it spreads throughout the water, so it is no longer possible to identify the place where the colorant was added. This is a slow process, however, and it might take months for the color to spread itself evenly. Gas molecules move faster and with much more freedom than molecules in a liquid, so diffusion is much faster in gases than in liquids.

A gas added to air diffuses through it fairly quickly, provided the volume of air does not extend very far vertically. If a column of air is more than about 3,000 feet (1 km) tall, diffusion will be affected by gravity and molecules will tend to sort themselves by weight. If the downward movement of air molecules under the influence of gravity is balanced by the upward movement of molecules drifting into a region containing fewer molecules per unit volume, the air is said to be in diffusive equilibrium. Diffusive equilibrium occurs above the turbopause (*see* ATMOSPHERIC STRUCTURE), at heights greater than about 60 miles (100 km). At lower levels, collisions between molecules contribute to the mixing of the atmospheric constituents, but the air in the upper atmosphere is so rare that molecules seldom collide. The overall effect of diffusive equilibrium is that the mean density of the atmosphere decreases with height and the heavier molecules are concentrated at lower levels, so the atmospheric constituents tend to separate by weight. The region in which diffusive equilibrium determines the atmospheric structure is known as the heterosphere. Several of the processes that are involved in diffusion, such as the MEAN FREE PATH or mixing length (*see* EDDY) of molecules together with their VELOCITY can be represented graphically in a diffusion diagram.

The capacity of an atmospheric layer to distribute infrared radiation (*see* SOLAR SPECTRUM) by diffusion is known as radiative diffusivity. This depends on the TEMPERATURE and AIR PRESSURE within the layer, and on the amount of WATER VAPOR the layer contains.

dimensionless number A quantity that is completely abstract, in that it is not a quantity of anything. The most familiar dimensionless number is π(pi), which defines the ratio of the diameter of a circle to its circumference.

Meteorologists use several dimensionless numbers, and they are extremely useful. The REYNOLDS NUMBER, used in calculations of fluid flow, is a dimensionless number. Others are the magnitude of the CORIOLIS EFFECT, which acts on bodies moving in respect of the surface of the Earth, and the ROSSBY NUMBER, which is used in calculations of the ACCELERATION of bodies that is caused by the rotation of the Earth.

diurnal Of the day, from the Latin word *dies,* which means "day." This can be interpreted in two ways. A diurnal animal, for example, is active by day, in contrast to a nocturnal animal, which is active only by night. In METEOROLOGY, however, diurnal refers to a phenomenon that occupies and is completed within a full 24 hours, counted from midnight to midnight, or that returns at intervals of 24 hours. An event or phenomenon that continues for 12 hours or occurs twice in every 24 hours is said to be semidiurnal. One that continues for or occurs at intervals of 3 days is terdiurnal.

The difference between the daytime and nighttime temperature for a particular place is known as the diurnal range. This may be calculated as the mean range, in which case the difference is between average temperatures, or the absolute range, in which case it is counted between the highest and lowest temperatures that have been recorded. In Atlanta, Georgia, for example, the mean diurnal range is 18°F (10°C) and the absolute range is 66°F (37°C).

Dobson spectrophotometer The Dobson spectrophotometer is an instrument that was invented in 1924 by the British physicist G. M. B. Dobson (1889–1976; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). It measures the intensity of different wavelengths of ultraviolet (UV) radiation (*see* SOLAR SPECTRUM), from which the concentration of OZONE present in the atmosphere can be inferred.

The spectrophotometer contains a photoelectric cell and a filtering device that allows UV radiation at four wavelengths to fall on the cell one at a time in a sequence. Of these wavelengths, two are absorbed by ozone and two are not. Those which are absorbed by ozone will give a lower reading than those which are not absorbed. The readings from the stronger wavelengths are gradually reduced until they equal those from the weaker wavelengths. From this, the ratio of the stronger to the weaker sets of readings can be measured and the concentration of ozone is inferred from the amount of radiation the ozone absorbs.

A spectrophotometer in Switzerland has produced continuous data on the OZONE LAYER since the 1920s. The instrument can use UV emitted by the Moon and stars as well as solar UV, but its measurements can be distorted by AEROSOLS and pollutant gases.

Doppler effect The rise in pitch of a sound that is approaching rapidly and the fall in pitch of a sound that is retreating rapidly. It was discovered by the Austrian physicist Christian Doppler (1803–53; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) and was first tested using sound, but the effect occurs with any form of wave radiation.

As the source of emission approaches, the distance waves must travel becomes progressively shorter. Their speed remains constant—at the speed of sound or the speed of light—but the number of waves reaching the observer each second increases (*see* WAVE CHARACTERISTICS). The distance between each wave crest and the next decreases, decreasing the wavelength and increasing the frequency. An increase in the frequency of a sound is detected as a rise in pitch. An increase in the frequency of a light beam is detected as a shift in the color toward the blue end of the spectrum. If the source of emission is retreating, the opposite occurs. The wavelength increases, frequency decreases, the pitch of a sound becomes lower, and light is shifted toward the red end of the spectrum. A Doppler effect is conventionally measured as an amount of blue-shift or red-shift and a moving object can be said to be red-shifted or blue-shifted.

downdraft A current of sinking air that is produced inside a cumulonimbus cloud (*see* CLOUD TYPES). Downdrafts usually travel at less than about 11 MPH (18 km/h), but can be much stronger in a SUPERCELL cloud. A typical multicell cumulonimbus cloud comprises a number of CONVECTION cells in each of which air is both rising and sinking, so the cloud contains several downdrafts.

The strong downdraft that occurs during the dissipation of a large cumulonimbus cloud is called a downrush. It is caused by the failure of the convective upcurrents that sustained the cloud. Snow and cold rain falling through the cloud chill the air, and this cools the warm air that is rising by convection, so it ceases to rise. There is then no mechanism for supporting the RAINDROPS and SNOWFLAKES. They all fall, as the cloud loses its moisture, producing a cloudburst (*see* SHOWER). As the raindrops and snowflakes fall, they drag cold air with them and it is this cold air that comprises the downrush.

A downdraft from a convection cell in a cumulonimbus cloud that reaches the surface and spreads to the sides is called a downburst. Downbursts produce strong gusts of wind and WIND SHEAR. In extreme cases a downburst from a supercell cloud can produce gusts of more than 75 MPH (121 km/h). If the downburst affects a surface area no larger than 2.5 miles (4 km) in diameter it is known as a microburst.

A macroburst is a strong downdraft of air that emerges from the base of a cumulonimbus cloud. It spreads to the sides when it strikes the ground surface, generating winds of up to 130 MPH (209 km/h) that can damage property within a range of more than 2.5 miles (4 km). A macroburst may continue for up to 30 minutes. It is similar to a microburst, but on a larger scale.

An air pocket is a downdraft that causes an airplane to drop briefly but suddenly with a motion that feels to the passengers like the descent of a fast elevator. In the early days of aviation it was supposed that the aircraft fell when it entered air that was insufficiently dense to support it. The air was likened to an empty pocket, and hence the name.

drag The retarding effect that is caused by FRICTION when air crosses a rough surface (*see* AERODYNAMIC ROUGHNESS). Surface winds and moving vehicles are slowed by drag, which acts as a force applied in the opposite direction to the motion. Frictional drag also moves objects, literally dragging them; the process is known as surface shearing stress (*see* SHEAR). Surface currents in the ocean are driven by the wind: the wind drags the water with it.

Drag also causes cumulonimbus clouds (*see* CLOUD TYPES) to dissipate. As RAINDROPS and SNOWFLAKES fall through the cloud, they drag with them the small pockets of air that surround them. This air is very cold. It chills the warm air that is rising by CONVECTION to feed moisture into the cloud. The loss of moisture causes the cloud to dissipate.

dropsonde An instrument package attached to a parachute that is dropped from an airplane. As it falls, the radio attached to the package transmits data on AIR PRESSURE, TEMPERATURE, and HUMIDITY recorded by its instruments at various altitudes.

A similar package that can be tracked to provide information on the wind speed and direction at different altitudes is called a dropwindsonde. Modern dropwindsondes are tracked by means of the Global Positioning System and are especially useful in studying TROPICAL CYCLONES.

A radiosonde is a similar package attached to a WEATHER BALLOON.

drought A prolonged period during which the amount of PRECIPITATION falling over a particular area is markedly less than the amount that usually falls in that place over the same period. A drought is longer than a dry spell (*see* WEATHER TERMS), but, obviously, the length of time without rain that is needed to define a drought varies greatly from place to place. In Britain, a drought is declared after a period of 15 days without rain. A drought is declared in the United States after a period of 21 days during which the precipitation does not exceed 30 percent of the average for that place and that time of year. In the northern Sahara, a drought is considered to exist if no rain has fallen for at least 2 years, and parts of the Atacama Desert in Chile have gone for 20 years without rain without this being considered a drought. Antofagasta, a city in the Atacama located on the Chilean coast and almost exactly on the tropic of Capricorn, has an average 0.5 inch (13 mm) of rain a year.

It is impossible, therefore, to define a drought in terms of absolute precipitation. The concept is more economic and social than meteorological. A dry spell becomes a drought when the lack of water threatens to restrict human activities. The authorities may ban the use of hose pipes for watering gardens and lawns or for washing cars, for example, so ornamental plants wilt and cars become dusty (but not mud-spattered, of course!). As the drought continues, the domestic water supply may be rationed and to prevent wastage the supply to private houses is sometimes shut down and standpipes installed in the street so people have to collect their water in containers.

During a drought, plant litter lying naturally on the ground becomes very dry. In this condition a LIGHTNING strike, the focusing of sunshine by a piece of glass such as the bottom of a bottle, or a carelessly dropped match or cigarette is enough to ignite the material. The resulting grass, heath, or forest fire can spread rapidly. There were severe wild fires in California in 1991 and between June and December 1997 forest fires that swept Indonesia spread to farms and destroyed crops, and produced a pall of smoke that seriously polluted the air over a large part of southeastern Asia. Although many of these fires were lit deliberately by farmers wishing to clear land, the vegetation was so dry following the prolonged drought caused by probably the most intense El Niño (*see* ENSO) of the 20th century that the fires raged out of control. The destruction of crops then contributed to a famine in which hundreds of people died.

The Palmer Drought Severity Index (PDSI) is an index for classifying droughts that was introduced in 1965 by W. C. Palmer, a meteorologist at the U.S. Weather Bureau. PDSI measures the extent to which the water supply departs from what is normal for a particular place and it is widely used in the United States for monitoring droughts. The index is calculated from the amount of precipitation, the temperature, and the amount of water available in the soil. However, the PDSI has several disadvantages. The values it uses are based on data from Iowa and western Kansas and are arbitrary. The index is sensitive to the water retaining capacities of soils so it is difficult to apply over a region containing soils of varying types. No allowance is made for the lag that occurs between precipitation falling and its runoff, and snow and frozen ground are not taken into account. The index centers on 0 and runs from 4.00 to -4.00.

PDSI Classification

4.00 or more	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient dry spell
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
-4.00 or less	Extreme drought

PHDI Classification

-0.5 to -1.0	Incipient drought
-1.0 to -2.0	Mild drought
-2.0 to -3.0	Moderate drought
-3.0 to -4.0	Severe drought
Greater than -4.0	Extreme drought (with some values as great as -7.0)

SPI Classification

Greater than 2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
Less than -2.0	Extremely dry

The PDSI measures meteorological drought. It has been modified to take account of soil moisture, stream flow, and lake levels by accumulating data, so the index based on long-term cumulative data measures what occurred in the past, providing a more accurate assessment of GROUNDWATER conditions. The revised version of the PDSI therefore measures hydrological drought. It is known as the Palmer Hydrological Drought Index (PHDI).

A team of scientists at Colorado State University have developed a Standardized Precipitation Index (SPI) based on the probability of precipitation. It claims to be simpler to use than the PDSI, and it can assess drought over different timescales.

Droughts can also be classified according to their types. In Britain, an absolute drought is a period of 15 consecutive days during which no rain falls.

An agricultural drought is one that causes a decrease in agricultural production. This is not the same as a meteorological drought.

A contingent drought, also called an accidental drought, is unpredictable, can occur anywhere, and its end is no more predictable than its start. If it is especially severe it is known as a devastating drought.

A devastating drought is a particularly severe contingent drought that occurs in summer and causes plants to wilt and die.

A hydrological drought is one during which the groundwater decreases and the water table falls markedly. This reduces the flow of streams and rivers. It can be caused either by a prolonged period without rain over the watershed supplying the groundwater or by an unusually low accumulation of winter snow in a mountainous region, leading to a reduced flow of melt water in spring.

An invisible drought is a drought in which precipitation falls, but when the amount of water lost by EVAPORATION and TRANSPIRATION is deducted, the amount of precipitation retained by the soil is insufficient to recharge AQUIFERS. Consequently, river levels and water tables remain low and plants continue to suffer stress. It is the kind of drought that often follows a more obvious drought, when there is little or no precipitation. Because there is precipitation, it is usually difficult to persuade people of the need to continue economizing in their use of water.

A meteorological drought is defined as a decrease in precipitation. This is not the same as an agricultural drought. Meteorological droughts are classified by the Palmer index.

A permanent drought is the type of drought that characterizes deserts. There are no permanent streams or rivers, precipitation rarely occurs, although it is often heavy when it does, and crops can be grown only on irrigated land.

A seasonal drought is less extreme than a permanent drought, but highly predictable, because it occurs in climates where all or most of the precipitation falls during one SEASON. Most plants native to such climates germinate and grow during the rainy season and survive the dry season as seeds or in a dormant state. In Mumbai, India, for example, 94 percent of the annual rainfall falls between June and September and the winter is extremely dry.

Further Reading

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Palmer, W. C. "Meteorological Drought," Washington, D.C.: U.S. Weather Bureau. *U.S. Department of Commerce Research Paper No. 45,* 1965.

dry ice Solid CARBON DIOXIDE (CO_2), which, at standard sea-level pressure, must be kept at a temperature below -109.3°F (-78.5°C, 194.7K) because at this temperature CO_2 sublimes (*see* SUBLIMATION).

When dry ice is released into the air, it has an immediate cooling effect. If the temperature of air that is almost saturated around the dry ice particles (*see* SATURATION) falls below -40°F (-40°C), WATER VAPOR instantly forms ICE CRYSTALS in the absence of FREEZING NUCLEI. This is because air that is close to saturation with respect to liquid water is supersaturated (*see* HUMIDITY) with respect to ice, and at below 32°F (0°C) air is always supersaturated with respect to ice. One gram (0.035 ounce) of dry ice falling through air with a temperature of 14°F (-10°C) and a relative humidity close to 100 percent will trigger the formation of about 100 billion (10^{11}) ice crystals before it sublimes. Once ice crystals have formed, water vapor will condense onto them. This removes water vapor from the air, leaving only ice crystals. These are fairly large and fall quite rapidly, gathering CLOUD DROPLETS as they pass through the lower, warmer parts of the cloud. This is the method used to seed clouds with dry ice (*see* CLOUD SEEDING).

Dry ice is also used to disperse cold FOG, in which the droplets are below freezing temperature. The dry ice particles initiate the formation of ice crystals, which grow at the expense of the supercooled water droplets (*see* SUPERCOOLING). In most cases the ice crystals quickly grow big and heavy enough to fall to the ground, clearing the fog, but even if they remain suspended in the air, the VISIBILITY improves markedly. This is because less light is scattered by a few large ice crystals than by many tiny water droplets.

Dry ice is also used to create theatrical effects. Released into the warm, moist air of a theater it immediately causes a cloud to form.

dry line (dewpoint front) A boundary that often forms over the Great Plains in spring and summer between hot, dry air to the west and warm, moist air to the east. The dry line develops over western Texas or eastern New Mexico, extending north into Oklahoma, Kansas, and Nebraska, and then moves eastward. Dry lines rarely occur east of the Mississippi River. Differences in the surface terrain between eastern Texas and the mountains of New Mexico provide the conditions in which dry lines form. Over New Mexico the barren ground is heated strongly. Over eastern Texas, clouds develop in moist air from the Gulf.

Advancing dry air lifts the moist air ahead of it, often producing huge cumulonimbus clouds (*see* CLOUD TYPES). Sometimes dry air about 1,000 feet (330 m) above the surface moves eastward faster than air at the surface. It overruns the lower air, causing a capping INVERSION. This inhibits the development of storm clouds, but storms develop very quickly if moist air penetrates the inversion.

The location of the dry line is commonly measured by comparing the dew point temperatures (*see* DEW) to either side. Ahead of the dry line these are commonly between about 60°F and 70°F (15°C–20°C) and behind it they are between 20°F and 30°F (between -7 and -1°C). The air temperature ahead of the dry line is usually between 70°F and 80°F (20–27°C) and behind it between about 85°F and 95°F (29°C–35°C). Storms associated with dry lines frequently become tornadic (*see* TORNADO).

dry season The time of year when PRECIPITATION is much lower than it is at other times. The dry season may occur in winter or in summer. Dry summers occur around the Mediterranean Sea and on the western sides of continents in latitudes 30–45°N and S. San Francisco, California, receives an average 22 inches (561 mm) of rain a year, but only 1.1 inches (28 mm) falls between May and September. Gibraltar, at the southern tip of Spain, has a very similar climate. Its average annual rainfall is 30 inches (770 mm), of which only 2.2 inches (56 mm) falls between May and September.

In regions with a MONSOON climate it is the winter that is dry. Mumbai, India, receives an average 71 inches (1,811 mm) of rain a year, but only 4 inches (104 mm) of rain fall between October and May.

A dry season has an effect on plants that is similar to that of a cold winter. In both cases, plant growth ceases for lack of moisture. In regions with a dry season, the aridity is caused by lack of precipitation. In regions with a cold season, it is caused by temperatures below freezing that turn liquid water to ice, rendering it unavailable to plant roots.

dust Solid particles that are lifted into the air by the wind or ejected as ash during volcanic eruptions. Certain industrial processes also generate dust that is removed in the flue gas (*see* AIR POLLUTION).

Airborne dust analysis is a technique for the sampling and categorization of dust particles that are seized from the air. Particles may be taken directly from the air or sucked from the surface of vegetation. They are then dried and graded according to their size, usually by shaking them through a series of increasingly fine sieves. They may also be classified by measuring their fall speeds (*see* TERMINAL VELOCITY).

The weight of dust that is suspended in a volume of gas, such as air or flue gas is known as the dust burden. It is measured in grams of dust per cubic meter at standard temperature and pressure (*see* UNITS OF MEASUREMENT). A dust collector is a device that removes dust from industrial waste gases. Electrostatic precipitators are used for this purpose. Filtration, impaction, and impingement (*see* POLLUTION CONTROL) are also processes by which dust may also be removed.

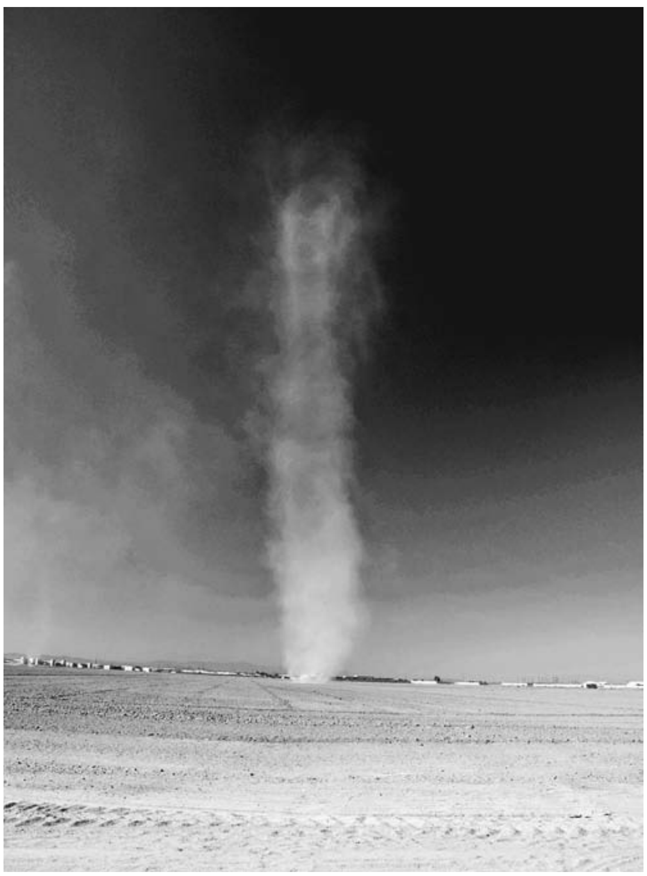
An increased concentration of dust particles often accumulates beneath an urban dome. This is known as a dust dome. CONVECTION due to the higher temperature of the URBAN CLIMATE generates surface winds blowing toward the center of the urban area. These winds carry dust from adjacent rural areas and also raise dust within the urban area, and the dust is kept airborne by the convection currents.

Air beneath a temperature INVERSION is sometimes made visible from a long distance by the dust that it holds. The upper surface of this dust-laden air, seen partly silhouetted against the sky, resembles a horizon. It is called a dust horizon.

Most dust consists of soil particles and the removal of soil by wind is the most widespread form of EROSION, the most extreme example of which affected the region of the United States which came to be known as the DUST BOWL.

Wind-raised soil particles are made from a variety of minerals, of which silica (silicon dioxide, SiO_2) is the most abundant. Soil particles range in size from those of clay (less than 2 µm across) and silt (2–60 µm) to fine sand (60–200 µm). In order for soil particles to be blown from the surface, the ground must be bare and dry. DESERTS are the main source of dust, but farming also contributes a large amount. The process of lifting is called deflation (*see* EROSION). The particles that become airborne most readily are about 40 µm in diameter. Particles larger than about 40 µm are too heavy to be lifted easily, and when they are lifted soon fall back to the surface. Very small particles are also difficult to lift because their large surface area in relation to their volume makes them tend to adhere to adjacent particles, and small particles are often sheltered by stones that are much too big for the wind to move. At higher wind speeds, however, both bigger and smaller particles will become airborne.

Dust can be carried for long distances, but eventually it settles. Sand dunes are accumulations of wind-blown sand, and fine soil, made from silt-sized particles, is deposited as a type of soil called loess, which is very fertile. There are large loess deposits in China, and loess covers much of the central United States. A belt of loess, very thick in places, lies along the eastern side of the Mississippi River in Mississippi, Tennessee, and Kentucky. It originated during the Wisconsinian GLACIAL, when the brief summer thaw caused valley GLACIERS to retreat, releasing water that flooded the flat-bottomed valleys. As the water drained away, the valley bottoms were turned into mudflats, and as these dried the wind carried away the dust.



A dust devil. Dust devils usually last for only a few minutes, but occasionally they can continue for 30 minutes or more. They rarely rise to more than about 300 feet (100 m) and can produce winds of 60 MPH (37 km/h) or more. (Stan Celestian, Glendale Community College, Arizona)

The local convergence (*see* STREAMLINE) of air may raise a spiraling column of blowing dust which has been lifted from the ground by the wind and is transported through the air, forming a dust devil. A dust devil is a twisting wind that resembles a TORNADO, but it is much smaller, a great deal less violent, and not associated with a violent storm. Dust devils rarely exceed about 300 feet (100 m) in height and they last for only a few minutes. WHIRLWINDS, which form under similar conditions, are much bigger and more destructive.

Dust devils are common in dry tropical and subtropical regions during the hottest part of the day, when the sky is clear. Unlike tornadoes, they rise upward from the ground, rather than descending from a cloud. A dust devil develops over a patch of ground that has absorbed more heat than its surroundings (*see* DIFFERENTIAL HEATING). The layer of air in contact with the hot ground is heated until its temperature is several degrees higher than that of the air above the surface layer. The lower air is then unstable (*see* STABILITY OF AIR) and begins to rise rapidly. This produces a very local area of low pressure into which air flows. VORTICITY causes the converging air to turn, and the conservation of its angular MOMENTUM accelerates it as it approaches the center of low pressure and its radius of curvature decreases. Close to the center, the air is drawn into the upward flow, which then begins to spiral. The flow is strong enough to carry dust and any loose, light material into the upward spiral. Dust devils may pass unnoticed if they occur over vegetation, where there is nothing they are able to lift. Dust devils die quickly because the upward movement of air carries away the excess surface heat that triggered them. Once the patch of ground cools to the temperature of its surroundings the dust devil has no source of energy to sustain it.

A dust whirl, also called a dancing devil, desert devil, sand auger, or sand devil, is a small column of rapidly rotating air that carries dust, sand grains, leaves, scraps of paper, and other light material. A small version of a dust devil, it is caused by convection above a patch of ground that has been heated more strongly than the surrounding area.

Wind blowing over a larger area may produce a dust storm, which begins as a strong wind that blows across bare ground in an arid region, where it lifts dust and keeps it aloft. Most airborne dust particles are less than 10 μm (0.004 inch) across and the frequent removal of fine particles explains why most desert surfaces consist either of bare rock or boulders, or of sand. A wind that blows over a sandy surface may cause a SANDSTORM, which differs from a dust storm only in the size of the particles it transports. The threshold velocity (*see* WIND SPEED) at which the wind begins to raise particles is proportional to the size of the particles and a moderate breeze of 13–18 MPH (21–29 km/h) is sufficient to raise dust.

Although it is moving, the dust will rise no more than a few hundred feet above ground level unless there are also vertical air currents to carry to a greater height. Consequently, major dust storms occur in unstable air. Then the dust can rise much farther, occasionally to 15,000 feet (4,600 m) or even higher, and it advances like a wall. A storm covering an area of 5,000 square miles (13,000 km^2) to a height of 10,000 feet (3,050 m) may carry 8 million tons (7.7 million tonnes) of dust. The fall speed of dust particles is only about 0.4 inch per second (1 cm/s). This means that once it is aloft dust can be carried a long distance, and when the vertical currents die it falls slowly and over a wide area.

Winds associated with an area of low pressure and that blow over a long distance often cause dust storms. The khamsin, ghibli, and shamal are winds of this type (*see* LOCAL WINDS). Dust raised by haboob storms (*see* LOCAL CLIMATES) in the Sudan is responsible for the dry HAZE over much of Central and West Africa.

A dust storm in which the dust consists mainly of dark-colored soil particles is known as a black blizzard. Such a storm occurred in May 1934, during the Dust Bowl drought. The black blizzard covered an area of 1.35 million square miles (3.5 million km^2), extending from Canada to Texas and from Montana to Ohio, and the dust cloud was 3 miles (5 km) tall.

Dust Bowl A region of the Great Plains in the United States, covering about 150,000 square miles (388,500 km^2) in southwestern Kansas, southeastern Colorado, northeastern and southeastern New Mexico, and the panhandles of Oklahoma and Texas, that experienced a severe DROUGHT from 1933 until the winter of 1940–41. During the drought, soil blew away as clouds of DUST that blanketed much of the eastern United States and extended far into the Atlantic.

Droughts in this region occur at intervals of 20–23 years, and they returned in the 1950s, 1970s, and 1990s. They vary in severity, but megadroughts, such as that of the 1930s, are known to have occurred in the 13th and 16th centuries and more recently in the 1750s, 1820s, and 1890s. Some of the earlier megadroughts lasted much longer than the drought of the 1930s. The 16th-century drought lasted for 20 years. Despite their recurrence, which is somewhat irregular, too little is known about what causes them for prediction to be possible.

The drought that gave the region its name of Dust Bowl caused much more human suffering than any other drought, because of the large agricultural population. From the middle of the 19th century, settlers were moving into the region and plowing up the natural grasses to grow wheat. Periodic droughts destroyed crops and ruined some farmers, but the return of the rains allowed farming to continue. Farming methods intensified during the early 20th century and the cultivated area increased. Cereal prices fell during the Great Depression that began in 1929, forcing farmers to cultivate the land even more intensively in order to maintain their incomes. They were able to do so because the annual rainfall from 1927 to 1933 was above average.

During this period the climate was becoming warmer. One consequence of the warming in middle latitudes was an increase in the number of days each year when the wind blew from the west. Westerly winds in North America lose their moisture crossing the Rocky Mountains and bring very dry air to the Great Plains. In 1933, the effect of this first became evident, when the annual rainfall was 7 inches (178 mm) below the average of 23 inches (584 mm). Crops started to fail, the natural grasses died back, and the land was left bare.

Natural prairie grasses bind the soil into large lumps that become very hard during drought. Over many years, cultivation had broken up these lumps, producing the fine soil texture that is needed for sowing, but when the land dried, instead of hard lumps the soil turned to dust. The loss of soil to the westerly winds was almost continuous, but the most severe dust storms were in May 1934 and October 1935. As well as soil, the wind carried away seed.

The Soil Conservation Service was established in 1935 in response to the tragedy of the Dust Bowl years, and the federal government began to teach and encourage practices to protect vulnerable soils. It was also recognized that on some prairie soils the natural grasses should be reestablished and the land should not be farmed.

Further Reading

Allaby, Michael. *Droughts*. Rev. ed. New York: Facts On File, 2003.

dynamic soaring A flying technique that is employed by some large sea birds, most notably the wandering albatross (*Diomedea exulans*), which has an average wingspan of 10 feet (3 m). The bird glides downwind from a height of about 50 feet (15 m) until it is very close to the sea surface. Then it turns into the wind to fly across the wind gradients behind wave crests or into the friction layer (*see* PLANETARY BOUNDARY LAYER). In doing so, it enters air that is moving more slowly than the air it leaves and this increases its speed in relation to the air (its airspeed). Increasing its airspeed increases the amount of lift generated by its wings, allowing it to climb back to its original height. In this way the bird can remain airborne for long periods with very little need to beat its wings.

E

Earth Observing System (EOS) Part of the Earth Science Enterprise, a program launched by NASA in 1991 with the aim of studying the Earth as an environmental system. The first part of the program involved collecting and studying data from a number of satellites. EOS forms the second part. It uses satellites dedicated to the task, the first of which was launched into polar ORBIT in 1999 and the second into a low-inclination orbit in 2000. The EOS will study the solid Earth, oceans, and atmosphere as an integrated system.

Further Reading

McClung, Alex. "The Earth Observing System." Goddard Space Flight Center. Available online. URL: http://eospso.gsfc.nasa.gov/eos_homepage/description.php. Updated January 24, 2006.

Earth Radiation Budget Experiment (ERBE) A study that uses both scanning and nonscanning radiometers (*see* SATELLITE INSTRUMENTS) carried on three satellites that measures all the solar radiation reaching the Earth and all the long-wave radiation leaving the surface. The aim of the ERBE is to determine, for a minimum of one year, the monthly average radiation budget on regional, zonal, and global scales, to determine the equator-to-pole energy transport gradient, and to determine the average diurnal variation of the radiation budget on a regional and monthly scale.

In the course of a month, the instruments provide measurements throughout almost the whole daily cycle for most regions of the Earth. The scanning radiometers transmit high-resolution measurements for each 2.5° latitude × 2.5° longitude region, and the nonscanning radiometers have a wide field of view (5° × 5° and 10° × 10°) that allows long-term monitoring on the scale of continents. The instruments are carried on the satellites NOAA 9, launched in December 1984, and NOAA 10, launched in September 1986, into Sun-synchronous ORBIT and the EARTH RADIATION BUDGET SATELLITE (ERBS).

Further Reading

NASA. "The Earth Radiation Budget Experiment." Available online. URL: http://asd-www.larc.nasa.gov/erbe/ASDerbe.html. Accessed February 14, 2006.

Earth Radiation Budget Satellite (ERBS) A satellite that is dedicated to the EARTH RADIATION BUDGET EXPERIMENT. It was launched by the Space Shuttle *Challenger* in October 1984 and is operated by NASA at the Goddard Space Flight Center. It travels in an inclined ORBIT, with an inclination of 57°. In addition to its ERBE instruments, the ERBS carries the Stratospheric Aerosols and Gas Experiment II (*see* SATELLITE INSTRUMENTS).

Earthwatch Program A program to monitor changes in the environment that was established in 1973 under the terms of the Action Plan that was agreed at the United Nations Conference on the Human Environment, held in Stockholm, Sweden, in June 1972. The Earthwatch Program is managed by the United Nations

Environment Programme (UNEP) and is based in Geneva, Switzerland.

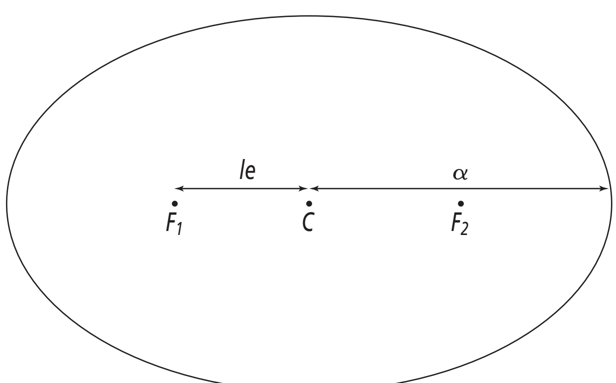
Further Reading

United Nations. "United Nations System-Wide Earthwatch." United Nations Environment Programme. Available online. URL: http://earthwatch.unep.net/. Last updated November 7, 2005.

eccentricity The extent to which the orbital path of a planet or satellite deviates from a circle. Planetary ORBITS are elliptical, and an ellipse is a geometric figure with two foci, so the bodies move about one focus of the ellipse. This is not located at the center of the figure, so the orbit is eccentric—it does not remain a constant distance from the geometric center.

Unlike a circle, an ellipse can vary in shape, becoming more circular or more elongated, and variations alter the distance between the orbiting body and the focus when the orbiting body is at its closest and farthest. The eccentricity of the Earth's orbit affects the amount of solar energy received at the surface at APHELION and PERIHELION and changes in eccentricity are linked to major changes in climate (*see* MILANKOVITCH CYCLES).

The extent of eccentricity can be measured. If the geometric center of the ellipse is C, and the focus about which the body orbits is F_1, the distance between C and F_1 is the linear eccentricity, le. The location of the second focus, F_2, is at the center of the major axis, α, from C to the point at which the orbiting body is furthest from F_1. Eccentricity, e, is then given by: $e = le/\alpha$.



Eccentricity is the extent to which the orbit of a satellite or planet deviates from a circle.

At present the eccentricity of Earth is 0.017. It varies over a cycle of about 100,000 years from 0.001, which is almost circular, to 0.054.

eclipse The temporary disappearance from the sky of either the Moon or the Sun as it is completely shaded by the passage of another body. When the Earth passes directly between the Sun and Moon, its shadow hides the Moon, producing a lunar eclipse. This does not occur at every full Moon, when the Sun, Earth, and Moon are aligned with the Earth in the center, because the lunar ORBIT is inclined at 5° to the Earth's orbit. Lunar eclipses occur when both the Earth and Moon arrive at one of the two points where their two orbits intersect when the Moon is full.

If they arrive at one of these points when the Moon is new, so the Earth, Moon, and Sun are aligned with the Moon at the center, a solar eclipse will occur. This is possible because, although the Moon is tiny when compared to the Sun, it is also much closer to the Earth. In fact, the diameter of the Sun is 400 times greater than that of the Moon, but the Sun is also 400 times farther from the Earth.

The eclipse will not be visible everywhere on Earth. The shadow of the Moon crosses the Earth along a track inside which the Sun will appear fully obscured for a length of time that decreases with distance from the center to the edges of the track. Outside the track, the Sun appears partially eclipsed over a much larger belt. If the track of the full eclipse misses the Earth completely, a partial eclipse may nevertheless be visible from some places.

Both the Earth and Moon follow ECCENTRIC orbits. Consequently, the distances vary between the Earth and Moon, and between both of them and the Sun. This alters the apparent diameter of the Moon and Sun as these are seen from Earth, by about 2 percent in the case of the Sun and 8 percent in the case of the Moon. If the three bodies are aligned at a time when the Moon is more distant from the Earth than the average 239,000 miles (384,000 km), its shadow will be too small to obscure the Sun completely. The center of the Sun will disappear, but a bright ring of sunlight will remain. This is known as an annular eclipse. If the alignment occurs when the Moon is closer than average to the Earth, the Sun will be obscured fully, producing a total eclipse.

During a solar eclipse, the shadow of the Moon traveling from west to east brings complete darkness and also a sharp drop in temperature. This produces a wind that may be felt either as itself or as a weakening or strengthening of the wind that was blowing before the shadow approached.

Ectasian The second of the three periods comprising the Mesoproterozoic era. The Ectasian began 1,400 million years ago and ended 1,200 million years ago. It was probably during the Ectasian that a single-celled eukaryotic organism (a cell containing a nucleus and bodies called organelles) merged with a cyanobacterium, which is a single-celled prokaryote (an organism lacking a cell nucleus and organelles) containing chlorophyll and capable of PHOTOSYNTHESIS. This merger of two distinct organisms (called endosymbiosis) led to the evolution of algae and green plants.

eddy Air that moves turbulently (*see* TURBULENT FLOW), its speed and direction changing rapidly and irregularly. The air movement is vertical as well as horizontal. The movement is also hierarchical, in that large eddies produce smaller ones in a cascade that ends only when the VISCOSITY of the air is sufficient to damp them out. This cascade was summarized in two lines of verse (reminiscent of a verse in *On Poetry* by Jonathan Swift (1667–1745), written by Lewis Fry Richardson (1881–1953; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). It is known as *Richardson's jingle:*

Big whirls have little whirls that feed on their velocity
And little whirls have smaller whirls, and so on to viscosity.

The cascading formation of ever smaller eddies diffuses the MOMENTUM of moving air, and also transports heat. This process is known as eddy diffusion, and it is due to eddy viscosity, which causes air to mingle at the boundaries between eddies. Intermingling transfers air that is moving along the path and at the speed of one eddy to another eddy that is moving at a different speed and in a different direction. This quickly diffuses the energy of the air, causing it to lose momentum, and transfers heat from the warmer to the cooler air. Eddy viscosity is many thousands of times more effective than molecular VISCOSITY as a mechanism for the transport of energy in air. The rate at which diffusion occurs is known as the eddy diffusivity and is measured in units of area per second.

Vertical air movement in eddies also carries water vapor. Measurements of the eddy viscosity are important in determining the rate at which water will evaporate into moving air and the extent to which wind will cool surfaces exposed to it. An evapotron is an instrument that is used to measure the extent and direction of this movement. This makes it possible to measure directly the rate of EVAPORATION over a very short period.

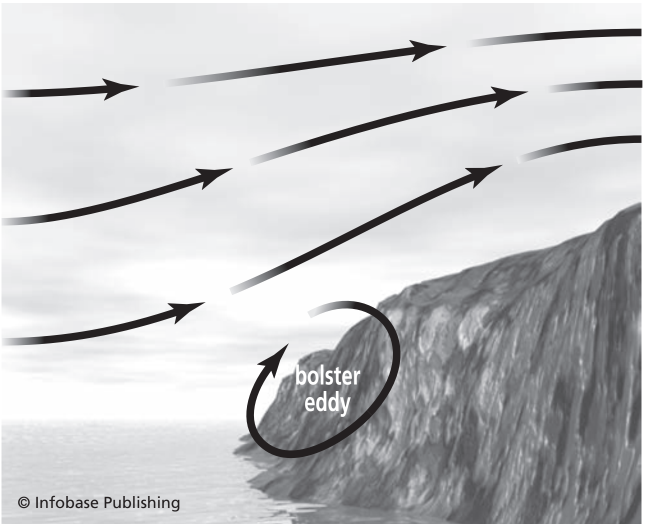
The average distance that a particle in an eddy travels perpendicular to the mean path of a turbulent flow of air is known as the mixing length. Eddies transport heat, water vapor, and momentum, so the mixing length is a measure of the distance to which eddy diffusion affects the air to either side of the eddy.

Moving air is subject to many disturbances, all of them producing eddies. As it flows across the surface of land or sea, but especially of land because the land surface is more irregular, the air nearest to the surface is slowed by FRICTION and air immediately above it tends to roll forward. This produces a ceaseless jostling among small pockets of air, with air descending on one side of each roll and rising on the other. Air flowing around a building also rolls, but about a vertical axis.

On a much larger scale, the GENERAL CIRCULATION of the atmosphere produces eddies and the ROSSBY WAVES that disrupt the ZONAL FLOW of air (*see* ZONAL INDEX) also produce eddy patterns. Large-scale midlatitude eddies are of major importance in the transport of heat from the TROPICS.

The effect of the sea surface on the air immediately above it is studied using a technique called eddy correlation. Eddy correlation involves measuring the mean speed and direction of air movement and comparing this with the fluctuations that occur in the vertical and horizontal components of that movement. Measurements are usually made at intervals of 30 to 60 minutes and at heights from 1.6 to 6.5 feet (0.5–2 m) above the water surface. The correlation is then calculated by applying mathematical equations.

A bolster eddy, also called a roll vortex, is an eddy that sometimes forms along the foot of a steep slope or cliff on the side facing into the wind. As the air approaches the slope, most of it moves upward and over the top, accelerating as it does so (*see* BERNOULLI EFFECT). Air rising up the slope enters a region of lower AIR PRESSURE. Its movement up the slope creates another area of reduced pressure near the base of the slope and some of the approaching air is deflected downward, toward this region of lower pressure. At the foot



Most of the air flows up the slope and over the top, but some is drawn down the slope and rolls over at the foot to form a bolster eddy.

of the slope the air starts to move horizontally in the opposite direction to the main flow of air. It becomes caught in the main flow, which curls it around into an eddy that is approximately circular in cross section.

Eddies produced when a wind carrying snow or sand is deflected by a wall, tree, or other obstruction often produce a shallow depression in the surface of the snow or sand at the base of the obstruction. This is called a wind scoop.

Ediacaran The final period of the NEOPROTEROZOIC era, which lasted from 630 million years ago until the beginning of the CAMBRIAN period, 542 million years ago. The Ediacaran derives its name from Ediacara, Australia, where there are fossils of about 30 genera of soft-bodied animals, some of them apparently unrelated to any modern groups. These animals lived near the shore of a shallow sea and seem to have been stranded in tidal pools that dried out and on mudflats. *See* APPENDIX V: GEOLOGIC TIMESCALE.

Ekman spiral The spiral pattern that emerges if the changing direction of the wind with increasing height is plotted on a two-dimensional surface. It is named after Vagn Ekman (1874–1954; *see* APPENDIX I: BIOGRAPHICAL ENTRIES), who discovered the similar spiral that appears when the changing direction with depth of wind-driven ocean currents is plotted.

Because of the CORIOLIS EFFECT, air does not flow directly from a region of high pressure to a region of low pressure. Instead, a balance is achieved between the Coriolis effect and the PRESSURE GRADIENT FORCE that causes the air to flow parallel to the isobars. This is the GEOSTROPHIC WIND, but it blows only above a height of about 1,650 feet (500 m), in the free atmosphere above the PLANETARY BOUNDARY LAYER. Below this height, FRICTION with the surface slows the wind. Slowing the wind reduces the magnitude of the Coriolis effect, thus increasing the pressure-gradient-force component and causing the wind to flow obliquely across the isobars (*see* ISO-). The angle at which it does so is proportional to the frictional drag and consequently is greatest at the surface, decreasing to zero above the boundary layer where the wind is geostrophic. At the surface the wind blows across the isobars at an angle of 10–20° over the sea and 25–35° over the land, where friction is greater. With increasing height, therefore, the wind direction changes in a spiraling fashion.

electric field A region in which a force is exerted on any electrically-charged body that enters it. The strength of the field is measured in volts per unit distance (*see* UNITS OF MEASUREMENT).

In the atmosphere, and at the ground and sea surface, there is a natural electric field, known as the fair weather electric field, with an average value of 37 volts per foot (120 volts per meter). The field is directed downward, carrying positive charge from the ionosphere (*see* ATMOSPHERIC STRUCTURE) to the ground. The strength of the field varies greatly in the vicinity of THUNDERSTORMS and is reduced by CONVECTION and RAIN. The rapid fluctuations in the vertical component of the electrical field that occur near the surface during a thunderstorm are called field changes.

The strength of the atmospheric electric field is measured by means of an instrument called an electrometer. Electrometers are raised a measured distance above the surface and then used to measure the change over time in the electric potential between the instrument and the surface. They are also used to measure the electric field between two balloons at different heights. The first electrometer is believed to have been the one used in 1766 by the Swiss naturalist Horace Bénédict de Saussure (1740–99; *see* APPENDIX I: BIO-

GRAPHICAL ENTRIES). An electrogram is a record that shows changes in the electric field over time.

When a dendrite (*see* ICE CRYSTALS) shatters in an electric field with a strength of several hundred volts per inch, the resulting fragments carry an electric charge. Such a fragment is called an electrification ice nucleus. Electric fields of this strength occur in cumulonimbus clouds (*see* CLOUD TYPES).

electron capture detector The electron capture detector is an instrument, invented by James Lovelock (1919–; *see* APPENDIX I: BIOGRAPHICAL ENTRIES), that can measure extremely small concentrations of substances in the air. It contains a radioactive source that emits a stream of electrons in an electromagnetic potential field. As a flow of air passes through the field, certain atoms present in the air capture electrons from the electron stream. This reduces the electric current by a measurable amount. The instrument is most sensitive to the halogens bromine, chlorine, fluorine, and iodine. This makes it very suitable for detecting the presence of organochlorine pesticides, such as DDT, and also CFCS.

***Elektro* satellite** A Russian WEATHER SATELLITE, known in the west as the *Geostationary Operational Meteorological Satellite,* that was launched from the Baikonur launch site on October 31, 1994, 15 years after its original planned launch date. It experienced problems with its sensors and did not reach its planned station in a geosynchronous ORBIT at 76°E until early December. It suffered continuing problems with its vertical sensor and failed to transmit useful images. The satellite was shut down in 1998. Its last known position was 71.89°E.

Elsasser's radiation chart A chart which is used to determine the components that together make up the outgoing radiation from the Earth's surface. There are several types, but the one most widely used in the United States was devised in 1942 by Walter Elsasser (1904–1991; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) and improved in 1960 by him and M. F. Culbertson.

The components of outgoing radiation are the total energy radiated from the surface, which is determined by the EMISSIVITY and TEMPERATURE of the surface, and the downward counterradiation from the atmosphere, which is determined by the air temperature, precipitable water vapor (*see* PRECIPITATION), and cloud cover. Radiosonde data (*see* WEATHER BALLOON) for the temperature and water-vapor content of the air at different heights are plotted onto the chart. This allows the effective infrared radiation from the surface, the net amount of radiation at a CLOUD BASE or cloud top, and the rate at which the surface is cooling by radiation to be determined.

emergency A situation in which people are at risk of injury or death and must move to a place of safety or receive immediate assistance or medical attention. Extreme weather conditions can cause emergencies.

A medical emergency can occur when a person remains outdoors in hot weather. Prolonged exposure to heat causes heat exhaustion. The patient has an accelerated pulse, cold and sweaty skin, may feel nauseated or vomit, and feels drowsy, although the body temperature remains normal. Drinking regularly to compensate for fluid lost by sweating prevents the condition occurring. Once it occurs, the patient recovers by resting somewhere cool. If heat exhaustion is prolonged, the patient may become apathetic, hysterical, or aggressive. The condition is then known as heat-neurasthenia.

Overheating can increase the blood flow to the skin while decreasing the flow to the brain. This can cause the patient to lose consciousness. The condition is known as heat collapse.

Extreme over-exposure to heat can cause heat stroke. This can be fatal. The body temperature rises, the skin feels dry, hot, and is usually flushed. The patient seems confused, lacks full control of the limbs, and may lose consciousness. Medical help must be sought immediately and the patient cooled gently, by loosening clothing, fanning, and sponging with cool (not cold) water.

Prolonged exposure to cold can cause hypothermia. The patient has a weak pulse, feels cold to the touch, speaks or behaves irrationally, and has difficulty with speech and vision. If untreated, hypothermia can be fatal. Treatment consists of gently warming the patient, but not by applying strong external heat, which can be dangerous.

Frostbite is physical damage to tissues that results from the loss of blood supply to a part of the body exposed to a very low temperature. The bodily extremities—ears, nose, cheeks, fingers, and toes—are the parts of the body most likely to be affected. The condition is painless, because there is no blood supply to the affected nerves, but the skin is locally very pale. This allows the early visual detection of frostbite and people outdoors by themselves in very cold weather are advised to carry a pocket mirror and regularly examine their faces and ears. In its early stages, frostbite can be treated by warming the affected parts in tepid water. Massaging is dangerous, because it may increase the tissue damage. If it remains untreated for too long, the tissue damage may be irreversible and necessitate amputation.

More widespread general emergencies are caused by FLASH FLOODS, violent STORMS, BLIZZARDS, TROPICAL CYCLONES (such as hurricanes), and TORNADOES. Warnings that are issued in advance of these events must be heeded.

emissivity The amount of radiation a body emits, expressed as a proportion of the radiation that would be emitted at the same wavelength by a BLACKBODY at the same TEMPERATURE. The emissivity of gases varies considerably with wavelength (*see* WAVE CHARACTERISTICS), but that of solid objects remains fairly constant. Taking account of emissivity (conventionally symbolized by ε) requires a modification of the STEFAN–BOLTZMANN LAW, so the equation becomes:

$$E = \varepsilon\sigma T^4$$

where σ is the Stefan–Boltzmann constant and T is the temperature in kelvins (*see* UNITS OF MEASUREMENT). The modification means that the Earth does not behave precisely as a blackbody; it is therefore described as a graybody.

A graybody is a body that absorbs electromagnetic radiation uniformly at all wavelengths. Consequently, its absorptivity (*see* ABSORPTION OF RADIATION) and emissivity are independent of the wavelength of the radiation. The emittance (E) of a graybody is given by:

$$E = \varepsilon\sigma T^4$$

where ε is the emissivity, σ is the Stefan-Boltzmann constant, and T is the absolute temperature (*see* TEMPERATURE SCALES). Many natural bodies are graybodies across a wide range of wavelengths.

For most surfaces, the emissivity is greater than 0.90, where blackbody emissivity is 1.0 (or 90 percent if blackbody emissivity is given a value of 100). The table below lists the emissivities of a range of common surfaces.

Typical Emissivities

Water	0.92–0.96
Fresh snow	0.82–0.995
Desert	0.90–0.91
Tall, dry grass	0.90
Oak woodland	0.90
Pine forest	0.90
Dry concrete	0.71–0.88
Plowed field	0.90

energy exchange The warming of a body that comes into contact with another body at a higher TEMPERATURE. Energy is exchanged between an AIR MASS and the land or sea surface beneath it. It is this exchange that gives the air mass its defining characteristics and that generates weather phenomena. As the air mass moves away from its source region this exchange alters until eventually the character of the air mass changes. Energy is exchanged between every surface and the air above it, except when the surface and the air are at the same temperature.

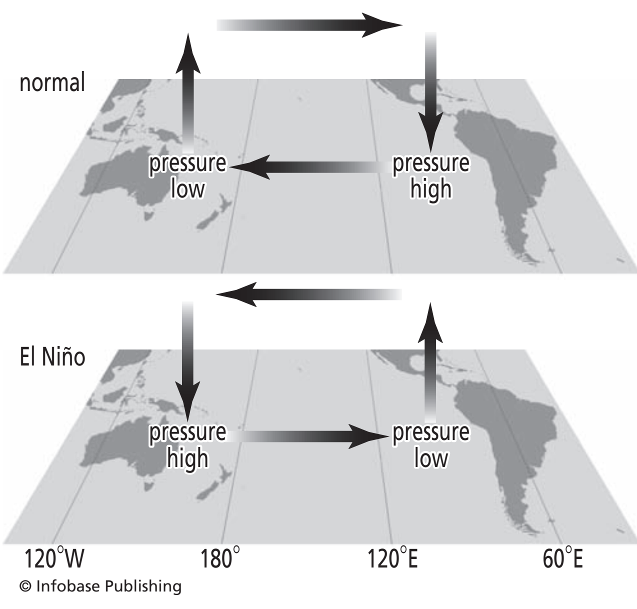
ENSO (El Niño–Southern Oscillation event) A change in the distribution of surface AIR PRESSURE and wind direction that affects the equatorial South Pacific Ocean at intervals of 2–7 years. In normal (non-ENSO) years the Hadley cell circulation (*see* GENERAL CIRCULATION) produces prevailing southeasterly surface winds (the *trade winds*). These drive the warm South Equatorial Current (*see* APPENDIX V: OCEAN CURRENTS), which flows from east to west, carrying warm water that accumulates as a relatively deep pool in the region of Indonesia. Off the South American coast the layer of warm surface water is much thinner.

Near Indonesia, the high sea-surface temperature warms the air. The rate of EVAPORATION is high and rainfall is heavy. In eastern South America, the prevailing winds blow from land to sea, crossing the Andes, and the coastal climate is extremely dry. Off the coast, the layer of warm surface water is thin enough to allow cooler water to rise close to the surface as a series of UPWELLINGS in the cold Peru Current, flowing northward from the Southern Ocean. The Peru Current is rich in nutrients, gathered as it moves across the ocean floor. These nourish a large planktonic population, which in turn sustains large numbers of fish and seabirds that feed on the fish.

At high level, the WALKER CIRCULATION carries rising air from the west to the east, where it sinks to the surface.

During an ENSO event, the pressure pattern changes. Surface pressure rises over Indonesia. This reduces the PRESSURE GRADIENT across the ocean and the winds weaken. As the winds weaken, so does the South Equatorial Current, allowing the layer of warm water in the east to deepen. This is the SOUTHERN OSCILLATION and, in a strong ENSO, the pressure distribution actually reverses, so there is high pressure in the west, low pressure in the east, and the flow of air at both high and low levels reverses direction.

This is the El Niño phase of the ENSO. While it lasts, warm water off South America suppresses the upwellings of the Peru Current. The plankton die or migrate elsewhere, followed by the fish and seabirds. Warm, moist air now flows toward the South American coast, bringing heavy rain to the coastal strip. There are also wider effects, including drought in northeastern South America, Indonesia, parts of Africa, and Australia, and heavy rain and storms in the western and southern United States. The extreme weather can also affect human health, through outbreaks of such diseases as malaria, Rift Valley fever, and possibly dengue or breakbone fever, which is an acute, infectious disease transmitted by mosquitoes. This is because the wet weather greatly increases the number of breeding sites for mosquitoes.



In the normal situation, surface pressure is high in the eastern Pacific and low in the western Pacific. This condition drives the air circulation, and the resulting wind drives a surface sea current flowing from east to west. During El Niño the situation is reversed.

The meteorological effects of this change usually appear at about Christmas (midsummer in the Southern Hemisphere), which is how the phenomenon earned its name of "(male) child" (i.e. the Christ child). It acquired this name because although El Niño brings hardship to fishing communities due to the disappearance of previously abundant shoals of fish, midsummer rain ensures a plentiful harvest for farmers. Consequently, farming communities regard El Niño as a Christmas gift.

With the passing of the El Niño, the situation returns to normal but may then swing into the opposite pattern, called La Niña. This brings a strengthening of the southeasterly winds, accelerating the warm surface current flowing from east to west. The pool of warm water near Indonesia deepens and rainfall there becomes heavier. Off the South American coast the water is cooler, the prevailing winds blow from the land towards the sea, and the weather is extremely dry.

The full southern oscillation, El Niño, La Niña, and final return to normal constitute the full ENSO event. El Niño is not always followed by La Niña, however, and La Niña sometimes occurs independently of an El Niño.

Especially strong ENSO events have occurred in 1982–83 and 1997–98. The event of 1997–98 was probably the strongest of the 20th century. It produced the highest average global temperatures for many years, and the Indonesian DROUGHT associated with it allowed wildfires to burn out of control, covering a large area of southeastern Asia with a pall of smoke.

ENSO events are not new. They are known to have been occurring for thousands of years. Other ENSOs, some continuing for longer than one season, have been recorded in 1396, 1685–88, 1789–93 (associated with the European crop failures that preceded the French Revolution), 1877–79, 1891–92, 1925–26, 1957–58, 1972–73 (associated with severe drought in the Sahel region of Africa), 1976–7, and 1986–87.

An explanation for the development of El Niño events, known as the delayed oscillator theory, proposes that these begin with an accumulation of warm water in the western equatorial South Pacific. The warm water accumulates because ROSSBY WAVES are reflected from the western boundary of the atmospheric system, causing KELVIN WAVES to propagate eastward, driving the cold water against the normal flow of the South Equatorial Current. This phenomenon gives rise to an El Niño.

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enthalpy The heat that can be felt (sensible heat) and that is transferred between bodies at different temperatures. It is defined as:

$$H = U + pV$$

where H is the enthalpy, U is the internal energy of the system, p is the pressure, and V is the volume. If p remains constant, U is equal to the HEAT CAPACITY at that pressure (c_p) and enthalpy is then

$$H = c_pT$$

where T is the temperature.

If energy is added to the system, either its internal energy increases or the system does some work according to the first law of thermodynamics (*see* THERMODYNAMICS, LAWS OF), which states that energy can neither be created nor destroyed. Provided no energy is added to air, its enthalpy remains constant and where changes are adiabatic (*see* ADIABAT) the enthalpy of the air is conserved and can be known from its temperature.

If MOISTURE is added, the heat capacity of water and the absorption and release of LATENT HEAT associated with PHASE changes modify the enthalpy of the air. The moist enthalpy for a specified mass of air is also conserved, but calculating it is more complicated. It is given by:

$$H = (c_p + m_tc_{pl})T + Lm_v$$

where m_t is the MIXING RATIO for the total amount of water in the air, c_{pl} is the heat capacity of liquid water, L is the latent heat of vaporization, and m_v is the mixing ratio of WATER VAPOR.

entrainment Mixing that takes place between a body of air and the air surrounding it. This happens when air rises by CONVECTION and the process can be inferred from the way a cumuliform cloud (*see* CLOUD TYPES) expands and dissipates at its edges. The cloud expands because the air in which it forms is expanding, and it does so partly by incorporating surrounding air. That air is drier than the air in which CONDENSATION is occurring and consequently cloud droplets EVAPORATE at the edges of the cloud.

Entrainment occurs whenever air moves vertically and as well as limiting the lateral expansion of cumuliform cloud it also contributes to the final dissipation of cumulonimbus cloud. Once PRECIPITATION commences, the falling ICE CRYSTALS, SNOWFLAKES, and RAINDROPS chill the air around them and drag cool air downward, forming downdrafts. The downdrafts are joined by cold, dry air that is drawn into the cloud from its surroundings. Because it is dry, the entrained air causes some of the precipitation to evaporate, drawing LATENT HEAT from the air inside the cloud and further cooling the downdraft. The air from the downdraft leaves the base of the cloud and spreads to the sides when it meets the surface below. This causes more air to be entrained and the downdrafts to increase. When the downdrafts dominate air movement inside the cloud, the cloud dissipates.

Eoarchean The earliest era of the ARCHAEAN eon, which began 3,800 million years ago and ended 3,600 million years ago. During the Eoarchaean the Earth's atmosphere consisted of nitrogen, methane, and ammonia.

Eocene The second of the three epochs that make up the NEOGENE period. The Eocene began 55.8 million years ago and ended 33.9 million years ago. The name means "dawn of the new," from the Greek words *eos* ("dawn") and *kainos* ("new").

It was a time of rapid mammalian evolution, during which horses, bats, whales, and other groups first appeared. Humid, subtropical climates extended as far north as southern Britain, which was covered by rain forest. These warm climates represent part of the PALEOCENE–EOCENE THERMAL MAXIMUM.

eolian **(aeolian)** Transported by the wind. The word is derived from the name of Aeolus, the Greek god of winds and son of Poseidon, god of the sea. In the *Odyssey* Homer tells how Odysseus met Aeolus, who gave him a bag of winds. When Odysseus's crew unwisely opened the bag, however, the winds blew their ship back to Aeolus, who refused any further help.

An eolian deposit consists of dust or soil that has been transported by the wind to the place where it is found. An eolian sand sheet is an area of sand that has been deposited by the wind. Such areas occur around the edges of areas covered with sand dunes. Eolian EROSION is another name for wind erosion.

ephemeris **(pl. ephemerides)** A table that sets out the height above the horizon (altitude), declination (*see* PLANE OF THE ECLIPTIC), and other data for astronomical bodies. An ephemeris showing the declination of the Sun for every day of the year is used in calculating the changing intensity of solar radiation at a particular location. The word *ephemeris* also describes a book that contains a collection of these and other astronomical tables.

equation of motion The mathematical equation that describes the movement of air according to Newton's second LAW OF MOTION. It is most often written as

$$a = F/M$$

where a is ACCELERATION and F is the force acting on a body of air with a mass M. The equation assumes that the mass of a PARCEL OF AIR remains constant and, therefore, the equation cannot be applied to the development of a cumuliform cloud (*see* CLOUD TYPES) in which the mass changes as a consequence of ENTRAINMENT.

The equation of motion can be broken down into its constituent elements of acceleration and force. Relative acceleration (a_r) is essentially linear and occurs as air moves in relation to the surface beneath. Acceleration due to the CORIOLIS EFFECT (a_c) takes account of the rotation of the Earth. The forces causing or affecting the movement of air consist of the PRESSURE GRADIENT FORCE (f_p), the gravitational force (f_g), and FRICTION (f_f). The pressure gradient force causes the air to move, the gravitational force acts vertically downward, and friction acts in the opposite direction to the movement of the air. Substituting these terms for those in the first equation, the equation becomes

$$a_r + a_c = f_p + f_g + f_f$$

equinox One of the two dates in each year when day and night are of equal length everywhere in the world, an interval of 12 hours passing between dawn (measured as the Sun appearing above the horizon) and sunset (measured as the Sun disappearing below the horizon), and 12 hours between sunset and dawn. At each equinox, the Sun is directly overhead at noon over the equator.

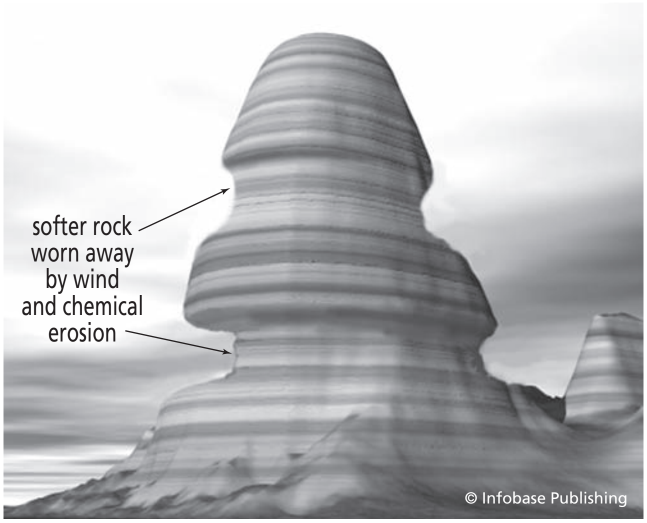
The equinoxes fall on March 20–21 and September 22–23. The length of the day varies because the rotational axis of the Earth is tilted (*see* AXIAL TILT) with respect to the PLANE OF THE ECLIPTIC, and this tilt produces the SEASONS.

erosion The wearing away of exposed rock surfaces and the removal of soil or other loose surface material by the action of wind and flowing water. Although the term is often used rather loosely, strictly speaking, erosion involves only the physical processes of wearing away. It is not the same thing as either WEATHERING or DENUDATION.

The removal of material from the land surface by the action of the wind is also called deflation. This can produce a depression in the surface, called a deflation hollow. Deflation is common on beaches, dry lake and riverbeds, and in DESERTS and deflation hollows are a feature of many sandy beaches.

Provided they are dry and not adhering to one another, mineral particles up to the size of sand grains move readily under pressure from wind and water. A wind of more than 15 MPH (24 km/h) is strong enough to produce a SANDSTORM. Once they are in motion, the particles are hurled against rocks and detach more particles from them. That is how rocks are eroded. It is a gradual process in which soft rocks erode first, leaving harder, more resistant rocks exposed.

Erosion can produce desert landforms with curious shapes. For example, a mushroom rock, also called a pedestal rock or rock mushroom, is an unstable rock formation that is often seen in deserts. It consists of a large rock that is mounted on a much narrower stem, so the rock is shaped like a mushroom. The most famous example is Pedestal Rock, Utah. The shape is the result of erosion combined with weathering. The wind blows away surrounding dust and sand, and wears away softer rock, leaving a column of harder rock exposed. When it rains, water is retained rather longer near the base of the rock than it is higher up



A mushroom rock results when chemical weathering wears away the base of the rock, leaving a large rock standing on a slim stem. The shape resembles a mushroom.

on the surface of the rock. Chemicals dissolve from the rock, form crystals as they dry, and the crystals are then blown away by the wind. This process of chemical weathering erodes the base of the rock faster than it erodes the rock above it.

A ridge with a sharp crest that is shaped by strong winds that blow predominantly from one direction is known as a yardang. A yardang will form in any rock that is only loosely structured. Yardangs are found only in very dry deserts with little plant cover and where soil has barely started to form.

Continued over millions of years, this kind of erosion has produced the sands of the deserts and, because water carries particles to the sea, the sands, gravels, and pebbles of riverbeds, beaches, and the ocean floor.

Extreme weather can cause erosion that is more rapid. Heavy rain and melting snow can wash exposed soil from hillsides. In this type of erosion the water cuts temporary channels that are left as barren, irregular gullies when dry conditions return, but that grow wider and deeper with every subsequent STORM.

If all the vegetation is removed and finely textured soil is allowed to become very dry, the slightest wind will lift it. DUST storms are fairly common, but the worst examples in modern times occurred in the 1930s on lands that became known as the DUST BOWL.

Erosion is a natural phenomenon. Nevertheless, poor farming practices can accelerate soil erosion and modern techniques aim to minimize it. Plowing is a major cause of erosion. Land is plowed in order to destroy weeds. The growing of crops that have been genetically modified to tolerate herbicides allows farmers to kill weeds chemically without risk to the crop and without having to plow. This has been found to reduce soil erosion considerably.

Rates of erosion are measured in bubnoff units, named after the German geologist S. von Bubnoff (1888–1957). One bubnoff unit (B) is equal to the erosion of one micrometer (1 μm = 0.00004 inch) per year, or one millimeter (1 mm = 0.04 inch) per thousand years. GLACIERS scour away the soil at a rate of about 1,000 B. In a temperate, maritime climate (*see* CLIMATE TYPES), soil erodes naturally at 1–5 B. Poor farming can cause soil to erode at 2,000 B or more.

Soil erosion is considered serious only if the rate at which the soil is being eroded exceeds the rate at which new soil is forming.

estivation (**aestivation**) A state of sluggishness or dormancy that occurs in some animals, including snails and lungfishes, when the weather is hot and dry. Estivation helps the animals to survive adverse conditions. It is analogous to HIBERNATION, by which some animals survive cold weather.

Eumetsat The European Organization for the Exploitation of Meteorological Satellites, an intergovernmental organization founded in 1986 that establishes and maintains operational meteorological satellites on behalf of 18 nations (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, and the United Kingdom). These nations fund Eumetsat operations. An additional 11 nations (Bulgaria, Croatia, Czech Republic, Hungary, Latvia, Lithuania, Poland, Romania, Serbia and Montenegro, Slovakia, and Slovenia) are classed as cooperating states. The satellites are operated from a control center in Darmstadt, Germany.

The Eumetsat Polar System (EPS) comprises three Meteorological Operational Satellites (Metop) that will be flown successively over a period of 14 years. The first of these satellites (Metop-A) was launched in 2006. Metop satellites orbit at a height of about 500 miles (800 km), allowing them to obtain much more detailed information about atmospheric temperature and moisture than the METEOSAT satellites, which are in geostationary ORBIT. The resulting data are processed by both Eumetsat and its partner, the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION. EPS is the European contribution to the INITIAL JOINT POLAR SYSTEM.

Eurasian high An area of high atmospheric pressure that develops across Eurasia in winter. It collapses fairly rapidly in April.

EUROCORE Project A European project that aims to collect data held at universities and other institutions within Europe, which is obtained from sediment cores and samples dredged from the sea bed and from ICE CORES. These are assembled into a directory that is published on the Internet and eventually will allow direct Internet access to the data.

Further Reading

EU-SEASED. "Eurocore Project Info." EU-SEASED. Available online. URL: www.eu-seased.net/eurocore/project_info.htm#seased1. Accessed June 6, 2006.

eustasy The worldwide change in sea level that is due either to tectonic movements of the Earth's crust (*see* PLATE TECTONICS) or to the expansion or melting of GLACIERS.

evaporation The change from the liquid to the gaseous PHASE. In the case of water, evaporation is the change from liquid into WATER VAPOR. Water is unusual among everyday chemical compounds in that it can exist in all three phases (solid, liquid, and gas) at temperatures commonly found at the Earth's surface.

Liquid water molecules are linked together by hydrogen bonds (*see* CHEMICAL BONDS) into small groups. The groups are constantly breaking and reforming, they can move freely, and they slide past one another. Molecules at the surface are held there by SURFACE TENSION. If the water is heated, its molecules absorb the heat energy and move faster. This increases the vapor pressure (*see* WATER VAPOR and SATURATION VAPOR PRESSURE) the molecules exert at the surface. When they have absorbed sufficient energy to sever the hydrogen bonds, molecules begin to break away from their groups and enter the air. The energy that is used to break the bonds between molecules is called LATENT HEAT and it does not raise the temperature.

In the thin BOUNDARY LAYER immediately above the liquid surface, the molecules add to the vapor pressure that is due to the water molecules already present. This pressure returns molecules to the liquid surface. Evaporation occurs if more molecules enter the air than leave it, so the amount of liquid decreases and the amount of vapor passing through the boundary layer increases. If the water surface is at a higher temperature than the air immediately above it, water molecules will always escape and evaporation will occur.

Wind reduces the vapor pressure in the air above the surface, thereby increasing the rate of evaporation. This is because wind generates a TURBULENT FLOW of air that removes moist air from above the liquid surface and replaces it with dry air. The rate of evaporation (E) can be calculated using Dalton's law of partial pressures (*see* GAS LAWS):

$$E = Ku(e_w - e_a)$$

where K is a constant, u is the mean wind speed, e_w is the vapor pressure at the water surface, and e_a is the vapor pressure in the air above the surface. Salt water evaporates more slowly than freshwater, by about 5 percent.

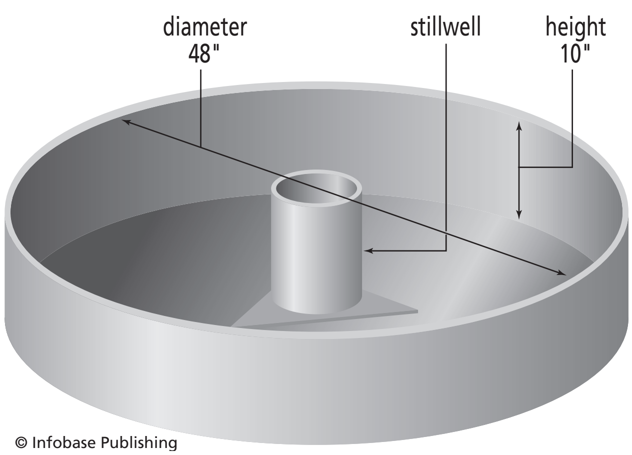
Alternatively, the Penman formula can be used. This is a mathematical formula for measuring the rate of evaporation from an open surface that was published in 1948 by the British climatologist H. L. Penman. The advantage of the Penman formula is that it expresses evaporation losses in terms of the duration of sunshine, the mean air TEMPERATURE, the mean HUMIDITY, and the mean WIND SPEED. The duration of sunshine is related to the amount of radiation received at the surface and the other factors limit the amount of heat and moisture that are lost from the surface. These four factors are regularly measured at WEATHER STATIONS and so the formula is easy to apply. It is also widely used in the construction of CLIMATE MODELS.

The ability of the climate of a region, or the weather at a particular time, to evaporate water is called its evaporative power, also known as evaporative capacity, evaporativity, and potential evaporation. It is measured as the rate of evaporation of chemically pure water from the surface at the temperature of the air in contact with the surface. Since in practice it is impossible to separate the rate of evaporation from an exposed water surface from the water leaving plants by TRANSPIRATION, evaporation and transpiration are usually considered together as EVAPOTRANSPIRATION.

There are several ways of measuring evaporation. An atmometer consists of a calibrated glass tube with one end that is open to allow water to evaporate.

An evaporation pan consists of a container of a standard size holding water that is exposed to the air. The U.S. Weather Bureau standard specification for an evaporation pan is for a cylindrical pan, 48 inches (1.2 m) in diameter, 10 inches (25 cm) deep, mounted on a platform holding it 6 inches (15 cm) above the ground. Usually, the pan is equipped with a stillwell. This is a device used to provide an undisturbed water surface for measurement. The standard stillwell is a metal cylinder 8 inches (30.32 cm) tall and 3.5 inches (8.89 cm) in diameter, open at both ends, that is mounted over a hole in a galvanized iron base. The base is fitted with leveling screws.

The pan is set in the open, filled with water to within 2–3 inches (5–7.5 cm) of the rim, and left for a convenient length of time. The exposure period, of one day, one week, or longer, must be sufficient for a reliably measurable amount of water to evaporate. The temperature and relative humidity of the air determine the rate of evaporation, so the period varies according to local conditions. The depth of water (in the stillwell if one is fitted) is measured at the start and end of the period and the change in depth is converted to the volume of water lost.



An evaporation pan is a container of standard dimensions that is used to measure the rate of evaporation.

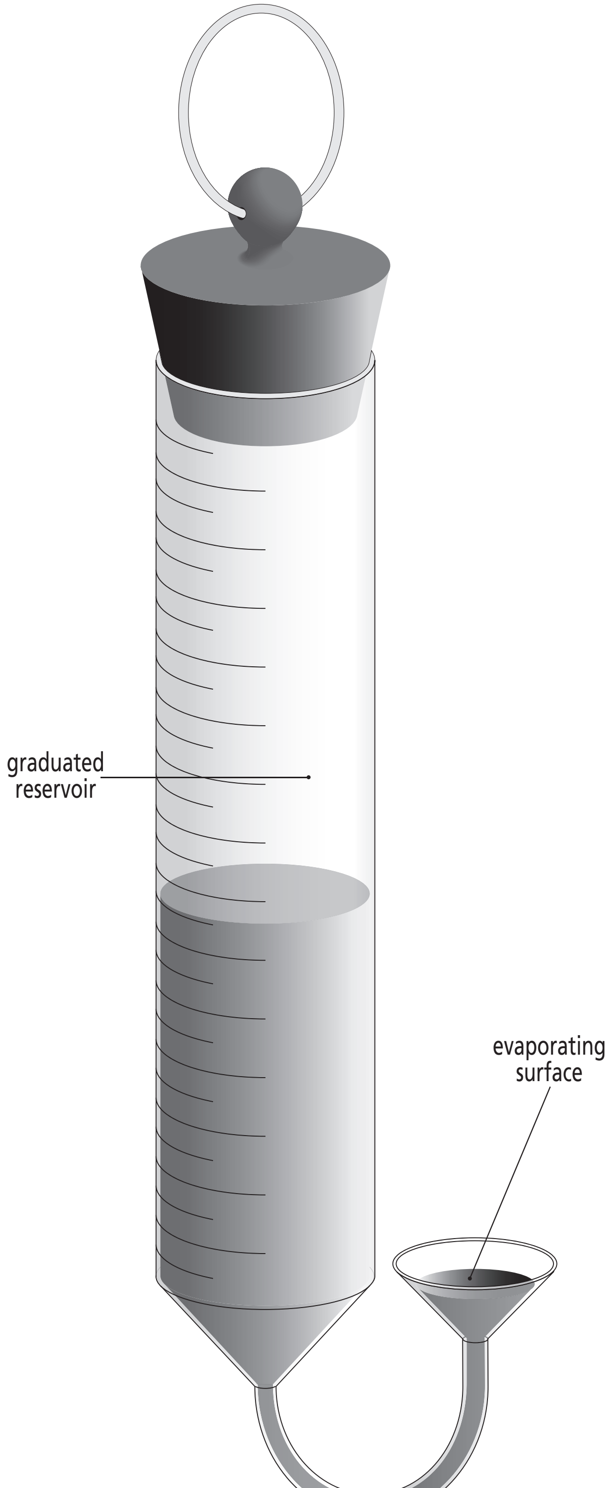
The surface of an evaporation pan may be covered by a screen made from wire mesh, usually ¼ inch (6 mm) gauge. It is then known as a screened pan. The mesh reduces INSOLATION and evaporation, producing a pan coefficient that is closer to unity than that from an unscreened pan. The pan coefficient is the ratio of the amount of water that evaporates from a unit area of the exposed surface of a large body of water to the amount that evaporates from an evaporation pan of similar area.

An evaporimeter is a simple instrument. There are several designs, but all of them measure the volume of water that evaporates from a known surface area over a measured period of time. An evaporimeter may be nothing more elaborate than an open dish of known surface area that is weighed periodically. It can be placed in the branches of a tree to measure evaporation above ground level. An alternative design consists of a graduated reservoir, sealed with a cork and with a ring from which it can be hung. At the bottom of the reservoir a U-tube expands to an open surface of known area that is covered with filter paper. As water evaporates from the filter paper, the level falls in the reservoir. For more precise measurements of evapotranspiration scientists use a lysimeter.

The evaporation of seawater leaves behind a deposit of mineral salts, known as an evaporite deposit. This occurs because evaporation involves the release into the air of water molecules from a body of liquid water. Substances dissolved in the water are left behind. Ordinary salt (NaCl) is the most common mineral salt to be precipitated in this way. Later geologic processes may convert an evaporite deposit into sedimentary rock.

Evaporites are precipitated when, over a prolonged period, the amount of water evaporating from a body of water exceeds the amount flowing into it and entering it from precipitation. In-flowing water carries dissolved salts, which are concentrated by the loss of freshwater through evaporation until the water becomes saturated. The salts then accumulate on the bed as the body of water gradually disappears.

The presence of evaporite deposits indicates that the area once lay beneath salt water and that a climatic or geologic change caused that water to evaporate. This can happen if the climate becomes warmer or the air over the water becomes drier. It can also happen if rock movements or a fall in sea level closes a narrow, shallow strait linking the water to a sea or ocean



In an evaporimeter, water is held in a graduated reservoir opening at the bottom into a U tube that expands into an evaporating surface of known area. The surface is covered by filter paper. There are several types of evaporimeter. This is the Piché evaporimeter.

from which it is replenished. There are large evaporite beds in Asia, Europe, and North America. The Bonneville saltflats in Utah are an evaporite deposit that was formed by the evaporation of LAKE BONNEVILLE.

Further Reading

Penman, H. L. "Natural evaporation from open water, bare soil and grass." *Proceedings of the Royal Society,* 193, 120–145.

evaporation pond An evaporation pond is an enclosed body of seawater that is allowed to evaporate in order to obtain the salts that crystallize from it. At one time this was the method by which almost all common salt (sodium chloride, NaCl) was obtained, and it is still used to produce sea salt in coastal areas that enjoy a hot climate.

evapotranspiration The loss of water from the surface due to the combined effects of EVAPORATION and TRANSPIRATION. Evaporation is measured fairly simply, using an evaporimeter or evaporation pan. It is more difficult to measure transpiration, but it can be done for an individual plant, although not for a stand of plants growing in the open. Measuring evaporation and transpiration separately introduces an element of artificiality, however, and for climatological or meteorological purposes it is unnecessary. Except in the most barren deserts, water vaporizing from the ground surface cannot be distinguished from water vaporizing from plants. The two processes are entirely distinct, but they both produce the same result, of adding water vapor to the air, and they both operate at the same time. Consequently, it is usual to consider them together, combining evaporation and transpiration as evapotranspiration.

Actual evapotranspiration (AE) is the amount of water that is lost from the ground surface monthly by the combined effects of evaporation and transpiration. In the THORNTHWAITE CLIMATE CLASSIFICATION this can be compared with the potential evapotranspiration (*PE*) to determine the amount of the water surplus or deficit present in the soil. This provides farmers with a guide to the need for irrigation.

Potential evapotranspiration (*PE*) is a concept that was introduced by C. W. Thornthwaite (1899–1963; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) into the second (1948) revision of his system of climate classification. It is the amount of water that would leave the ground surface by evaporation and transpiration if an unlimited supply of water were available. This is equivalent to the amount that would evaporate from an open water surface. It is calculated in centimeters from the mean monthly temperature in °C, corrected for the day length. Provided the monthly temperatures are known the value for *PE* can be read from tables. The equation for calculating potential evapotranspiration is:

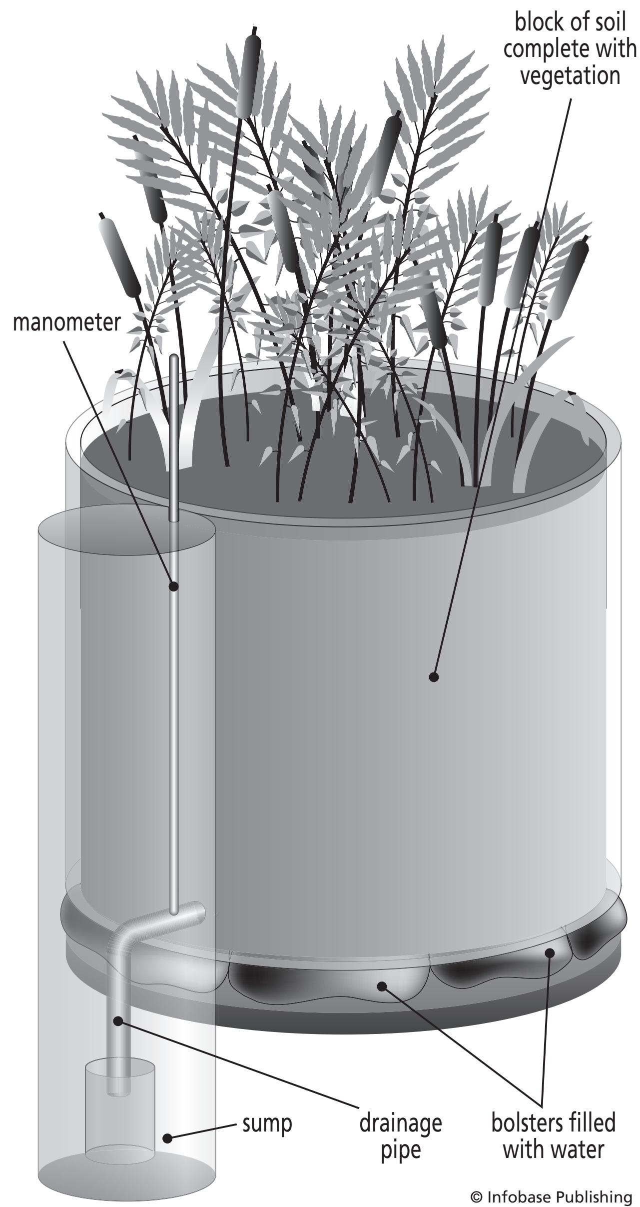
$$PE = 1.6(10t/I)^a$$

where t is the mean monthly temperature, I is the sum for 12 months of $(t/5)^{1.514}$, and a is an additional complex function of I.

There are several ways to measure evapotranspiration directly. An evapotranspirometer is an instrument that measures the difference between the amount of water reaching the surface as PRECIPITATION and the amount that percolates downward through the soil, assuming the amount of moisture that is retained by the upper soil remains constant. Two devices are installed, because the average of the two readings provides a more reliable measure than the reading from one device alone.

For each installation, a 6-inch (15-cm) layer of gravel is placed beneath an enclosed block of sandy loam soil 18 inches (45 cm) deep, 22 inches (56 cm) wide, and covered with vegetation 2 inches (5 cm) tall. Galvanized iron piping, its end protected by a fine gauze filter, leads down an incline from the base of the gravel to a collecting can placed at the bottom of a pit and closed by a lid. The collecting cans contain the water that has percolated through the soil over a convenient period (a day, week, or month depending on the amount of precipitation). If this value is subtracted from the amount of precipitation over the same period, the remainder is equal to the amount of evapotranspiration. This is then converted into a standard unit of millimeters per day.

A lysimeter consists of a block of soil together with all the plants growing in it that is held within a waterproof container with only the upper surface open to the air. Strictly, the lysimeter is the block of soil, but the term is usually applied to the whole device. The container is usually circular and should be not less than 3.3 feet (1 m) deep and 3.3–20 feet (1–6 m) in diameter. A lysimeter installed in a forest may contain a mature tree, so the dimensions of its container must be sufficient to accommodate the root system. Water may be prevented from draining from the base of the soil block by means of an impermeable membrane, or a drainage pipe may be fitted and water allowed to drain naturally into a sump, where the amount of drainage can be measured. The



A lysimeter measures changes in the amount of water in a block of soil, complete with its vegetation, held in a waterproof container. Drainage water is fed into a sump and measured. In this design, changes in the mass of the soil block are registered as changes in pressure and monitored by a manometer. In other designs the soil block is weighed.

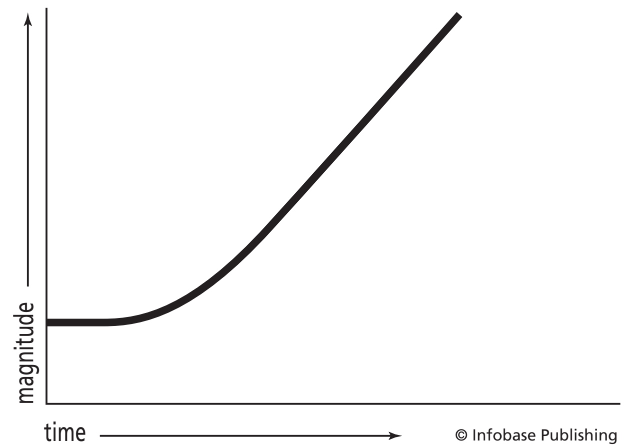
amount of water that enters the soil block from precipitation, including dew, and irrigation is measured. Any change in the mass of the soil block must be due to the entry of known amounts of water or to losses by evapotranspiration. Changes are measured either by a balance system, which measures the weight of the soil block, or as changes in pressure at the base, which are measured by a MANOMETER. Lysimeters can produce very precise and reliable data, but they are large and require very careful installation and maintenance. Consequently, they are used mainly at agricultural research stations.

exitance (**emittance**) A measure of the amount of electromagnetic radiation that is released from a unit area of a surface. The exitance of the photosphere of the Sun is about 70 MW/m^2. Multiplied by the area of the photosphere, this figure indicates that the total solar output is about 4.2×10^{20} MW.

expansional cooling The mechanism by which an expanding fluid loses heat. Expansion means that the molecules making up the fluid move farther apart. In order to do so, they must push other molecules out of the way. When molecules collide, KINETIC ENERGY is transferred from one to another. If the colliding molecules remain in the same body of fluid and at a constant temperature, the amount of kinetic energy remains unchanged, because no energy is lost in the transfer of energy between molecules. In an expanding fluid, however, the molecules in one body of fluid (the expanding body) transfer kinetic energy to outside molecules (in the surrounding fluid). Consequently, energy leaves the expanding body. The loss of kinetic energy means the molecules move more slowly.

When molecules collide with a surface, such as that of the bulb of a thermometer or of heat sensors in human skin, the impact is less violent than it was formerly. This is measured by the thermometer and felt by the skin as a drop in temperature. The opposite happens when a fluid is compressed. This is known as COMPRESSIONAL WARMING.

exponential An adjective describing a function that varies as the power of a particular quantity. If $x = y^a$, x is said to vary exponentially with a. An exponential change is one in which a quantity changes by a constant proportion that is calculated in each period on the accumulated total of the changes in previous periods.



An exponential growth curve begins with a very shallow rise that quickly becomes almost vertical.

Suppose, for example, that an initial value of 1,000 increases by 20 percent in each period. At the end of the first period the 1,000 will be equal to 1,000 + 200 (20 percent of 1,000) = 1,200. At the end of the second period the 20 percent will be calculated from the new total of 1,200, so 1,200 + 240 = 1,440. Over a number of periods, therefore, the sequence will be: 1,000, 1,200, 1,440, 1,728, 2,073.6, etc. Although the rate of change (20 percent in this example) remains constant the accumulating total grows increasingly rapidly.

At a 20 percent rate of increase, a quantity will double in 3.5 periods. The number of periods that are required for the initial quantity to double is approximately equal to 70 divided by the rate of increase; in the example 70 ÷ 20 = 3.5. Plotted as a graph, an exponential curve has a characteristic J-shape. It grows slowly at first, but then more rapidly until it rises almost vertically. An exponential decrease produces a curve of similar shape, but that falls rather than rises. The decay of radioactive substances proceeds as an exponential decrease.

extratropical hurricane A severe storm that occurs in the Arctic or Antarctic. The term was first used in 1954 by Tor Bergeron (1891–1977; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) to describe arctic storms. The CYCLONES that produce extratropical hurricanes are seldom as much as 620 miles (1,000 km) in diameter, and some are no more than about 185 miles (300 km) across. Pressure at the center falls to around 970 mb, and they produce winds of about 45 MPH (72 km/h) gusting to 70 MPH (113 km/h).

Although these winds are much less severe than winds of hurricane force (more than 75 MPH (121 km/h) on the BEAUFORT WIND SCALE) such storms resemble TROPICAL CYCLONES in certain respects. Their sustained winds follow a circular path with a calm eye at the storm center, they produce clearly defined spiral bands of cumulonimbus cloud (*see* CLOUD TYPES), and air flows outward from them at high level, producing cirrus cloud. They extend to the tropopause (*see* ATMOSPHERIC STRUCTURE) and dissipate rapidly if they cross over land.

Extratropical hurricanes differ from tropical cyclones in other respects. They develop much more quickly, reaching their full strength in 24 hours or less, travel much faster, at up to 35 MPH (56 km/h), and they survive for only 48 hours or less before crossing a coast and dissipating. Tropical cyclones can spend a week or longer crossing the ocean.

Extratropical hurricanes form where there is a low-pressure disturbance close to the edge of the SEA ICE and where streams of air with very different characteristics merge along an arctic FRONT. In both cases the effect is to draw cold air from above the ice and air from above the sea that may be 72°F (40°C) warmer.

extreme The highest or lowest temperature that is observed at a particular place over a specified period. Contrasted with the average daily temperature for the hottest or coldest month, the extreme represents the range of temperatures that are possible. In New York City, for example, July is the hottest month and January the coldest. The average maximum temperature in July, measured over 40 years, is 85°F (29°C), and the highest temperature recorded (the extreme) is 106°F (41°C). The lowest average temperature in January, over the same 40-year period, is 27°F (-2.8°C), and the coldest extreme is -15°F (-26°C).

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fallout The removal from the air of solid particles that descend to the surface by gravity, a process known as gravitational settling. The rate at which particles fall varies inversely with their mass, large particles settling faster than small ones, but it is also influenced by the wind and EDDY diffusivity. Particles are also removed from the air by impaction (*see* AIR POLLUTION), rainout (*see* CLOUD CONDENSATION NUCLEI), and washout (*see* RAINDROPS).

The lower boundary of an area of fallout is called the fallout front. The fallout front marks where solid particles that are descending by gravity reach the surface. A wind that carries particles that are at the same time descending to the surface by gravity is known as a fallout wind.

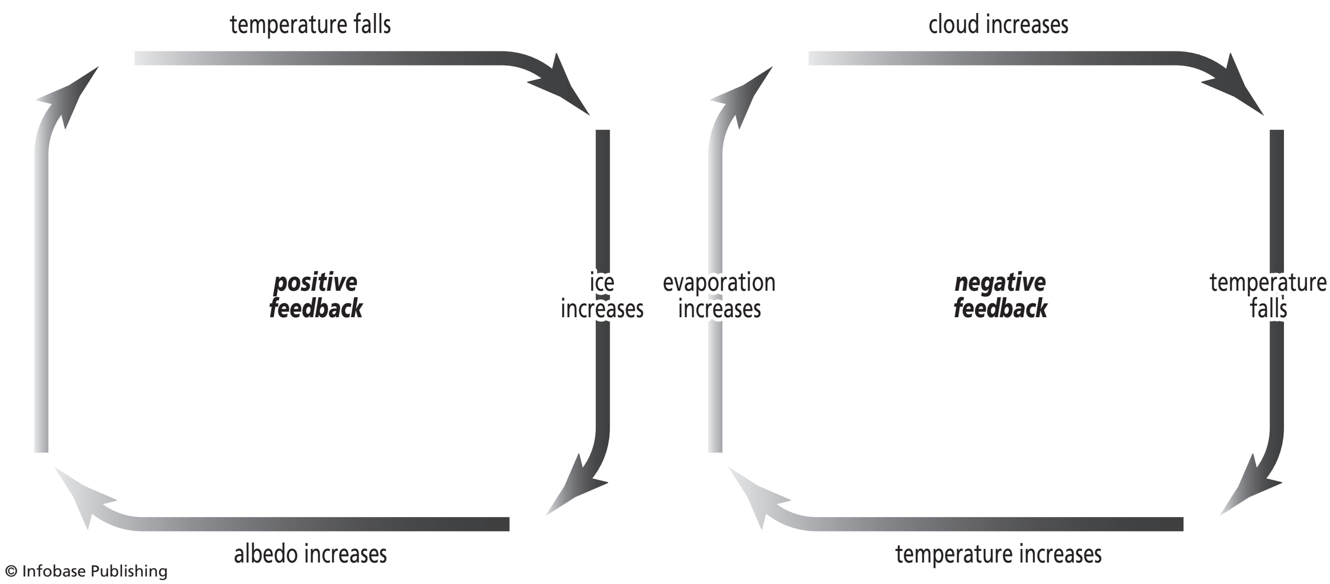
feedback The behavior of a system that is regulated by a part of the system itself, so that a signal generated by a component of the system affects the whole. The concept is derived from engineering. When steam engines were first employed to drive factory machines, it was very important that they ran at a constant speed. The speed of a steam engine is regulated by the opening and closing of a valve that allows steam into the cylinders. To maintain a constant speed, engines were fitted with devices called governors. These were weights mounted on the ends of arms. The arms were pivoted and attached to a rotating vertical axis, and they were linked to the valve by levers. If the engine speed increased, the weights spun faster and were thrown outward. This moved the levers in such a way that the valve descended, reducing the supply of steam. If the engine ran more slowly, the weights fell inward, raising the valve and increasing the steam supply.

Feedback can be positive or negative, and the governor of a steam engine worked by negative feedback. It is called negative because the response of the system (in this case the engine) is to reduce the activity of the component that generated the signal. If the engine ran faster, the governor slowed it, and if it ran more slowly, the governor accelerated it.

Like all natural systems, the climate is also subject to both positive and negative feedback. The idea of a SNOWBLITZ is based on positive feedback. It proposes that a fall in temperature leads to an increase in the area covered by snow and ice. This increases the ALBEDO of the planet. More solar radiation is reflected rather than being absorbed, and so the temperature falls further.

If the temperature increases, on the other hand, it may be checked by negative feedback. In this case the increase in temperature leads to an increase in the rate of EVAPORATION. The atmosphere contains more water, so CONDENSATION also increases and clouds form. Clouds reflect solar radiation, and this cools the surface.

Although feedback mechanisms are extremely important, in reality their effects are not simple. A rise in temperature increases evaporation, for example, but WATER VAPOR is the most powerful of all greenhouse gases (*see* GREENHOUSE EFFECT), so it may cause the atmosphere to warm and the feedback to be positive. Whether the feedback effect of clouds is positive or negative depends on



In positive feedback, falling temperature causes the temperature to fall further. In negative feedback, a rising temperature is checked.

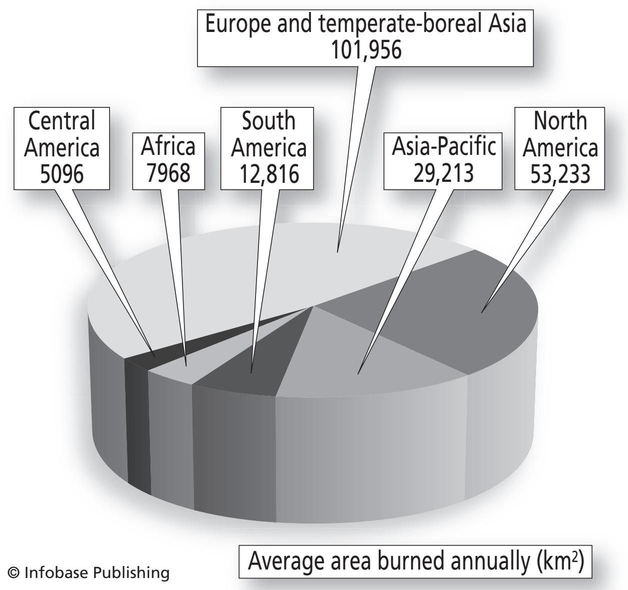
the type of cloud. Clouds reflect sunlight, which is negative, but are composed of water, which absorbs radiation and so the effect is positive. Cirriform clouds (*see* cloud types) are too thin to have a major effect on the albedo, but they are able to absorb radiation and so they tend to have a warming effect. Low clouds are usually thicker and more reflective, and so they have a cooling effect.

In the snowblitz example, the positive feedback may also be increased by the reduction in evaporation as the temperature falls. Cold air is drier than warm air and so the greenhouse warming effect decreases as the temperature falls.

Fennoscandian ice sheet The ice sheet that covered northern Europe during the most recent Pleistocene ice age, known as the Devensian Glacial period in Britain, the Weichselian elsewhere in northern Europe, and the Würm in the Alps. At its greatest extent the ice sheet covered all but the southernmost part of Britain, all of Scandinavia, Belgium, the Netherlands, and about half of Germany and Poland. Everywhere from the North Cape, in the far north of Norway, to Kiev on the banks of the River Dnieper in Ukraine, lay beneath ice.

The maximum extent of the Fennoscandian ice sheet that covered Europe from the North Cape to the Dnieper during the last glacial period

fire The burning of vegetable matter releases gases, including carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen oxides, and a range of organic compounds. Some of these are harmful to human health. Fires also release particulate matter (*see* air pollution). Airborne particles act as cloud condensation nuclei, but those released by fires include very fine particles with diameters smaller than 2.5 μm



The average area of vegetation that is burned each year, by continent (1 km^2 = 0.386 mi^2)

(0.0001 inch) that are believed to cause respiratory damage.

Most fires in remote areas are caused by LIGHTNING, but in populated areas most are started by people, accidentally or deliberately. Fires occur every 1–3 years in forests that grow in MONSOON climates, and in North America and Eurasia 12–50 million acres (5–20 million ha) of forest burn out of control every year. During the 1982–83 El Niño (*see* ENSO) about 35 million acres (14 million ha) of forest and cropland burned in Borneo and Indonesia. During the hot, dry summer of 2000, wildfires swept across the western United States, consuming almost 1 million acres (600,000 ha). In the world as a whole, vegetation covering an average of 81,269 square miles (210,282 km^2) is burned every year.

An intensely hot fire may trigger a firestorm. During World War II, bombing raids in which very large numbers of incendiary bombs were dropped with the intention of starting fires caused firestorms in Hamburg and Dresden, Germany, and in Tokyo, Japan. The atomic bomb that was dropped on Hiroshima also caused firestorms, and the one dropped on Nagasaki may have done so.

Firestorms occur because hot air rising by CONVECTION from the fire creates local areas of low AIR PRESSURE. The hotter the fire, the more vigorous are the convectional upcurrents and the lower is the pressure at the base. Air is drawn in at the base to fill the low pressure, and if the fire is hot enough the air enters as a gale-force or even hurricane-force wind (*see* BEAUFORT WIND SCALE). The in-flowing air delivers oxygen to the flames, fanning them to still higher temperatures. As the air approaches the low-pressure center, convergence (*see* STREAMLINE) starts it rotating cyclonically (*see* CYCLONE). The wind picks up any loose material lying in its path and carries it into the fire. Much of this debris is likely to be flammable, so the wind also feeds fuel into the fire. The firestorm is then self-sustaining and continues to burn until it exhausts its supply of fuel or heavy PRECIPITATION lowers its temperature.

The heat of a firestorm is often great enough to ignite other fires some distance away. In this case ignition is due not to sparks or burning fragments falling onto objects or structures, but to radiant heat. Just as a piece of paper held close to a hot fire will burst into flames before the fire touches it, so objects some distance from the storm will start to burn.

Weather conditions that favor the ignition and spread of forest fires in a specified area are described as fire weather. When there is a risk of fire, a fire weather forecaster at the NATIONAL WEATHER SERVICE issues a fire weather watch. There is a serious fire risk between fall and early spring, when deciduous trees are leafless, if the sustained average wind speed is 15 MPH (24 km/h) or more, the relative HUMIDITY is 25 percent or less, and the temperature is greater than 75°F (24°C).

A forest crown fire on Pueblo Mountain, Oregon. ***(US Bureau of Land Management/Scott Moore, Photographer)***

firn SNOW that is still lying on the ground during the second winter since it fell, having failed to melt during the intervening summer. As further falls of snow cover it during succeeding winters, firn is compressed until its DENSITY reaches 50–52 pounds per cubic foot (800–840 kg m^{-3}). The snow is then impermeable to both air and water and is known as glacier ice.

The firn line, also called the annual snow-line or firn limit, is a line on a GLACIER that marks the highest elevation at which snow that falls during the winter melts during the summer. Snow above the firn line becomes firn. The firn line is often clearly visible, because above it there is clear, blue ice and below it there is snow.

The period of one year that commences with the start of snow accumulation at the firn line of a glacier is called the budget year. The year continues through the following summer, when snow is lost by ABLATION, and so a comparison of measurements taken at the start of successive budget years indicates the growth or diminution of the glacier.

flash flood A severe flood that occurs very suddenly when extremely heavy rain, usually a cloudburst (*see* SHOWER), falls on high ground, delivering water much faster than it is able to soak into the soil and be dispersed safely. Prolonged rain that fell earlier may have left the ground saturated, so additional water cannot drain through it, but flash floods can be caused by rain falling on dry ground if the water falls faster than it can soak away. In that case the water may fill previously dry gullies, turning them into torrential streams. In either case, water flows across the ground surface, moving downhill with sufficient energy to dislodge and transport soil, rocks, and sometimes trees. The flood may then advance as a front, resembling a wall of water, up to 20 feet (6 m) high, moving at 25 MPH (40 km/h) or more.

In the summer of 1996, light rain that suddenly grew into a huge cloudburst sent water, rocks, and mud through a campsite and trailer park at Biescas in northern Spain. Trees were uprooted and, carried by the water, tents, campers, and trailers were swept away, and more than 70 people died.

Flohn classification A CLIMATE CLASSIFICATION that was proposed in 1950 by the German climatologist Professor Hermann Flohn. It is a genetic classification, which means it is based on the influence of AIR MASSES and prevailing winds (*see* WIND SYSTEMS). It is considered one of the best schemes of this type and especially useful as an introductory outline of climate classification.

Flohn divides the climates of the world into eight groups. These are based mainly on the global wind belts and the type and amount of PRECIPITATION that each receives.

1. Equatorial western zone, where the climate is constantly wet.
2. Tropical zone, dominated by the winter trade winds, where rain falls mainly in summer.
3. Subtropical dry zone, dominated either by the trade winds or by the SUBTROPICAL HIGH, where the climate is arid.
4. Subtropical winter-rain zone, where the climate is of the Mediterranean type (*see* CLIMATE TYPES) and rain falls mainly in winter.
5. Extratropical westerly zone, where there is precipitation throughout the year.
6. Subpolar zone, where there is little precipitation, but it is distributed throughout the year.

6a. Boreal, continental subtype, where rain falls in summer and a limited amount of snow falls in winter.

7. High polar zone, where precipitation is very low, falling as rain in summer and snow in winter.

Further Reading

Flohn, H. "Neue Anshcauungen über die allgemeine Zirkulation der Atmosphäre und ihre klimatische Bedeutung" ("New Views of the General Circulation of the Atmosphere and its Climatic Significance"). *Erdkunde (Earth Science),* 3:141–62.

flux The rate at which a fluid or radiation flows across an area. In the case of a VECTOR QUANTITY, the flux is calculated as the rate of flow past a line that crosses the area at right angles to the direction of flow, multiplied by the area. In the case of radiation, flux is measured as the number of particles per unit volume and their average velocity.

flying conditions The operation of modern aircraft is much less constrained by weather conditions than was the case during the early years of aviation. By the late 1940s, cockpit instruments allowed pilots to take off without being able to see the runway, provided they were able to taxi the aircraft onto the runway and align it. The next advance came with the development of RADAR, which makes it possible for aircraft to land in poor visibility. Even today, however, the safety of aircraft and their crews depends critically on accurate weather forecasts, and trainee pilots study meteorology to ensure they understand and can interpret forecasts correctly. Meteorological services prepare routine aviation forecasts.

Over the years, aviation meteorology has accumulated a number of specialist terms. Some of these refer to the limits set for safe aircraft operation.

The poorest weather conditions in which aircraft are permitted to fly under visual (VFR) or instrument (IFR) flight rules is called the weather minimum.

Meteorological minima are the lowest values for VISIBILITY, CLOUD BASE, and other relevant features of the weather that are prescribed for specified types of flying operations. Operational weather limits are the minimum values for CEILING, visibility, and WIND at a particular airfield that will permit aircraft to take off and land safely. The fitness figure or fitness number is a value used in Britain that is calculated for the suitability (fitness) of weather conditions for the safe landing of aircraft at an airport. The value takes account of visibility, cloud base, and crosswinds. *Below minimums* is the term that describes conditions of visibility, cloud base, and wind that are less than the minimum standards laid down for aircraft to take off and land.

A local extra observation is a weather observation that is taken at an airport at frequent intervals, often of 15 minutes, when conditions are close to the minima for taking off and landing and when flight operations are imminent. The observation includes visibility, ceiling, cloud amount, and such other details as may be relevant. A special observation is an observation of a particular weather condition affecting the operation of aircraft that is made because of a significant change since the most recent report. The change might be a lowering or rise in the cloud ceiling, improvement or deterioration in visibility, or a fall in temperature that causes ice to form on the runway.

VFR weather describes weather conditions in which the surface visibility and cloud base allow aircraft to take off, land, and cruise under visual flight rules (VFR), which mean their pilots require no assistance from ground-based guidance systems and there is no restriction on the airfields they can use. Visual flight rules apply when the surface visibility is at least 3 miles (5 km) and the cloud base is no lower than 1,000 feet (300 m). Under poorer weather conditions pilots must operate under IFR terminal minima.

IFR terminal minima are the conditions of minimum surface visibility and cloud base under which aircraft are permitted by law to approach an airfield and land under instrument flight rules (IFR). These conditions vary according to the ground-based guidance systems available at the airfield, the type of aircraft, and the level of qualification in instrument flying held by the pilot.

Instrument flying is the operation of an aircraft when the pilot cannot see the horizon or the ground and is consequently unable to judge the attitude of the aircraft (whether or not it is flying straight and level) visually. Under these conditions the pilot must rely wholly on information supplied by the flight instruments. The aircraft is then subject to instrument flight rules (IFR). These lay down the minimum conditions under which a pilot possessing a particular level of qualification may fly an aircraft of a particular type. If an aircraft is to take off under IFR from one airfield and land under IFR at another, the pilot must file an IFR flight plan. This sets out the route to be followed, the height at which the aircraft will fly, and the estimated time of arrival at the destination airfield. A copy of the flight plan is sent to the ground controllers at the destination airfield.

The visibility that is measured from an airfield control tower is called the control-tower visibility. Ground visibility is the horizontal visibility that is measured at ground level or at the height of an airfield control tower (when it is synonymous with control-tower visibility). Ground visibility affects the movement of aircraft while they are taxiing on the ground and during takeoff and landing. Runway visibility is the horizontal visibility along an airfield runway, measured by an observer in a specified position looking along the runway in the direction of takeoff and landing. The runway visual range is the greatest distance along an airfield runway at which the runway lights are visible to the pilot of an airplane that has just touched down and is decelerating in its landing run. Flight visibility is the forward visibility from an aircraft that is in flight.

A runway observation is a measurement or assessment of a meteorological condition that is made at a specified position on or close to an airfield runway. Runway observations are usually made of WIND SPEED and direction, AIR PRESSURE (which affects pressure altimeters), TEMPERATURE, PRECIPITATION, cloud base, and horizontal visibility. The air temperature measured about 4 feet (1.2 m) above the surface of an airfield runway is called the runway temperature. This is used in calculating the DENSITY altitude. Runway temperature is reported to pilots if the density altitude may differ from the value they expect.

A tailwind or following wind is a wind that blows in the same direction as that in which a body is traveling. If the body is traveling along the surface of the land or sea, the assistance provided by a tailwind reduces the amount of fuel that must be consumed to maintain a given speed and that accelerates wind-powered transport such as sailing ships and yachts.

Aircraft measure their speed as the speed at which they move through the air. This is known as their airspeed; their speed in relation to the surface is known as their ground speed. A tailwind does not alter the airspeed, because it is the air surrounding the aircraft that moves, carrying the aircraft with it. The speed at which the aircraft moves through the air is unaltered, but its ground speed is increased to a value equal to the sum of the airspeed and the speed of the tailwind or of the tailwind component of a wind blowing at an angle to the direction of flight. The opposite of a tailwind is a headwind. Its speed or component of its speed is deducted from the airspeed to give the ground speed. The term following wind is also applied to a wind that blows in the same direction as that in which waves are moving over the surface of the sea.

A crosswind is a wind that is blowing neither in the same direction as a moving object such as an airplane (a tailwind), nor in the opposite direction (a headwind). Consequently, there is a component of the wind that acts perpendicularly to the object's direction of motion. The component of the wind direction that is aligned parallel to the track over the land or sea surface that an aircraft pilot plans to follow is called the route component. The component is calculated from the average wind direction along the entire track at the altitude the aircraft will fly. If the component is in the direction of the flight (a tailwind), it is termed positive, and it is negative if it is in the opposite direction (a headwind).

The upward vertical component of a GUST of wind that would produce a given ACCELERATION on an aircraft flying straight and level through air of a constant density at the recommended cruising speed of that aircraft is called the effective gust velocity.

The sector wind is the average direction and speed of the wind that is blowing over one sector of the route an aircraft pilot intends to follow at the altitude the pilot plans to fly. The section of the route is called a sector because traditionally it is drawn on a map with two lines drawn at an angle (usually 5°) to either side. This makes it simpler to plot the location of the aircraft and interpret this as the number of degrees it is off its course and, from that, the correction that should be made to the aircraft heading. The sector wind may be either observed or calculated from the broader SYNOPTIC situation.

Cloud top is the highest altitude at which there is a perceptible amount of a particular cloud or cloud layer (*see* CLOUD BASE). An aircraft flying above the cloud top is said to be "in the clear," although there may be another cloud layer above.

The corrected altitude, also called the true altitude, is the altitude of an aircraft measured by an ALTIMETER and adjusted to take account of the difference between the ambient temperature and the temperature of the standard atmosphere (*see* UNITS OF MEASUREMENT).

Icing describes the formation of ice on the surfaces of the leading edges of the wings, tailplanes, and tail fins of aircraft. It occurs when an airplane flies through air containing supercooled water droplets (*see* SUPERCOOLING) and its own exposed surfaces are below freezing temperature. The droplets then freeze instantly on impact and ice can accumulate extremely rapidly. This is dangerous, because the shape of the ice coating can significantly alter the aerodynamic properties of aerofoil surfaces, so the airplane loses lift, and the weight of the ice can overload the mainspar that supports the wings. Most large aircraft are equipped to prevent icing by heating the affected surfaces or by using de-icing boots. These are flexible tubes running along the leading edges of vulnerable surfaces and covered by a flexible outer skin. Air is pumped through the tubes to expand and contract them one at a time, the movement breaking the ice, which is then swept away by the flow of air. The icing level is the lowest altitude at which an aircraft is expected to experience icing in a particular locality under the prevailing weather conditions.

fog Fog is PRECIPITATION in the form of stratus cloud (*see* CLOUD TYPES) that extends to the ground or sea surface and that reduces horizontal visibility to less than 1,094 yards (1 km). Cloud that reduces visibility less than this is often called mist. Fog consists of fog droplets. These are water droplets 0.00004–0.0008 inch (1–20 μm) in diameter. In a typical fog there is less than 0.001 ounce of water in every cubic foot (1 g/m^3) of air. If pollutants, such as soot particles, are mixed with the water droplets the fog is called SMOG. A well-defined mass of fog that is seen from a distance, especially at sea, is called a fog bank. A fog streamer is a wisp of fog that forms near the surface when cold air blows across a lake. Several fog streamers sometimes merge to form a steam devil.

Water that is deposited on trees and other tall structures by FOG and that drips to the ground is known as a fog drip. A fog drip can deliver as much water to the ground as a light shower. It is common in the redwood groves of northern California.

Ground fog is any type of fog that covers less than 60 percent of the sky. Ground fogs are often very shallow, sometimes not extending as far as the head of a person walking through them. Shallow fog does not reduce horizontal visibility above a height of 6 feet (1.8 m) above the surface. Sometimes shallow fog completely hides the ground, but rises no higher than a person's knees, and it forms when the sky above is blue and cloudless. Fog of this kind is almost always radiation fog.

A fog horizon is the boundary between the sky and the upper surface of a layer of fog that is trapped beneath an INVERSION. The boundary is seen from a position above the fog, where it resembles the true horizon. The fog conceals the true horizon. A fog horizon can be misleading, because the flat, featureless surface of the fog may not be horizontal.

Fog forms either when air is cooled to below its dew point temperature (*see* DEW), or when EVAPORATION adds WATER VAPOR to the air, increasing its relative HUMIDITY to SATURATION. Fogs formed by cooling are classified according to the mechanism that causes the cooling as advection fog, radiation fog, and hill fog (or upslope fog). Fogs caused by evaporation are classified as frontal fog and steam fog. Arctic sea smoke is a type of steam fog.

Freezing fog forms when the air temperature is below freezing. The low temperature chills surfaces to below freezing and fog droplets freeze onto them. The droplets themselves may be supercooled (*see* SUPERCOOLING). Freezing fog coats surfaces with ice and makes driving conditions hazardous by icing the windshields of moving vehicles.

Advection fog in an Arizona valley, with a rocky peak rising above it. ***(Historic NWS Collection)***

Frozen fog is a low cloud consisting of ICE CRYSTALS. It forms when supercooled water droplets freeze. The crystals then grow by the Bergeron–Findeisen mechanism (*see* RAINDROPS), and they soon become heavy enough to fall. Consequently, frozen fog usually clears quickly. Supercooled fog over airfields is sometimes cleared by seeding it with DRY ICE to accelerate this process.

Ice fog forms when relatively warm water is suddenly released into very cold air. This happens when sluices are opened in a dam. These are located low on the dam wall and the water they release is from deep below the lake surface, where the water is warmer than the surface water. As this water encounters the very cold air—the temperature must be lower than -22°F (-30°C)—evaporation is rapid, because the vapor pressure (*see* WATER VAPOR) at the water surface is much greater than it is in the cold, dry air. Only a small amount of water vapor is required to cause saturation, however, and so water vapor freezes, rapidly forming a fog of ice crystals by DEPOSITION. Arctic mist is a very thin ice fog that sometimes occurs in high latitudes when the air temperature is well below freezing. It reduces visibility only slightly.

Frost smoke is a type of steam fog that forms when the temperature is well below freezing. Its particles are ice crystals rather than water droplets. A steam devil is a stream of fog that forms an almost vertical column of cloud over the surface of an unfrozen lake in winter. Steam devils develop when cold, dry air crosses the lake and is warmed by contact with the water surface. Water evaporates into the air and the warmed air rises. It cools adiabatically (*see* ADIABAT) and its water vapor condenses into streamers of fog. Where warm air is rising especially vigorously, a number of streamers may be drawn into the upcurrents to form a steam devil, which is rather similar to a DUST devil.

Advection fog forms when warm, moist air is carried horizontally across a cold surface by a wind of about 6–20 MPH (10–32 km/h). This can happen in summer, when the land has been warming through the day much faster than water nearby and air then moves from the land over the water. It also happens when air crossing relatively warm sea encounters a current carrying cold water. Air crossing the Pacific Ocean encounters the cold California Current (*see* APPENDIX VI: OCEAN CURRENTS) off Cape Disappointment, Washington State, making this the foggiest place in the United States. The warm, moist air is chilled when it comes into contact with the cold surface. This increases its relative HUMIDITY to 100 percent and its water vapor starts to condense, producing the fog. Turbulence in the wind carrying the air causes mixing. This carries cool air to a greater height, thus extending the height at which fog forms, and it also carries the fog itself to greater heights. Advection fogs can be 2,000 feet (610 m) deep.

Sea fog is a type of advection fog that forms at sea when warm, moist air moves over an area of much colder water. As the air is chilled to below the dew point temperature by contact with the cold water, some of the water vapor it carries condenses. Fog of this type is common in certain sea areas, especially off the eastern coast of Newfoundland, where air moving northward crosses the warm water of the Gulf Stream and then encounters the cold water of the Labrador Current.

Arctic sea smoke is fog that forms when very cold air that has crossed ICE SHEETS and GLACIERS moves from the land across a sea surface that is 36°F–54°F (20°C–30°C) warmer. Because the air is very cold, it contains little water vapor. In the layer of air immediately adjacent to the much warmer water, the amount of water vapor needed to cause saturation is much greater than the water-vapor content of the air. Consequently, water evaporates rapidly into the air and then rises by CONVECTION. This carries it into the cold air, where it condenses again to produce cloud. The "smoke" is often very dense, but it usually extends to a height of no more than about 35 feet (10 m).

Bora fog is a dense fog that forms when a strong bora wind (*see* LOCAL WINDS) lifts clouds of spray from the sea.

Cacimbo is a heavy mist or wet fog associated with low stratus cloud and sometimes drizzle (*see* PRECIPITATION) that occurs along the coast of Angola during the dry season. The cacimbo usually forms in the morning and evening and may penetrate inland for some distance. It helps prevent extreme DROUGHT. The cacimbo is caused by onshore winds that carry warm air across the cold Benguela Current.

California fog affects the coastal regions of California and drifts through the Golden Gate, at San Francisco, nearly every afternoon between May and October. It is an advection fog driven by a sea breeze (*see* LAND AND SEA BREEZES). As the land warms during the day, air above it rises and cooler air is drawn in from over the sea. The air over the Pacific Ocean is relatively warm and moist, but as it approaches the coast the air crosses the cold California Current. The resulting drop in its temperature causes the condensation of some of the water vapor it carries, and this produces the fog.

Frontal fog, also called precipitation fog, is associated with a FRONT, where warm air is being lifted above colder air. The warm air cools as it rises, and when its temperature falls below the dew point temperature, its water vapor begins to condense. Cloud forms and may produce rain. The rain, falling from warm air, crosses the front into the colder air below. A BOUNDARY LAYER of air around each raindrop is warmed by contact with the water, and once its temperature rises it is able to contain more water vapor than the colder air around it. Raindrops evaporate rapidly, and the air

Sea smoke over open water along the edge of the Ross Ice Shelf, at the Bay of Whales. ***(Michael Van Woert, NOAA, NESDIS, ORA)***

containing them mixes with the surrounding air. Mixing raises the relative humidity of the cold air, and if it exceeds 100 percent, the water vapor will start to condense again, but this time to form cloud beneath the front. The effect is to produce cloud that extends from ground level to the cloud above the front.

High fog develops on the upper slopes of a mountain and sometimes extends as stratus cloud over the valley on the LEE side.

Hill fog, also called upslope fog, forms when moist air is made to rise, causing it to cool adiabatically (*see* ADIABAT). If it cools to its dew point temperature, water vapor will condense. This is the only type of fog to be caused by adiabatic cooling. Hill fog occurs on hillsides, but also on the Great Plains of North America, when moist air from the Gulf of Mexico moves westward across the continent, up a gentle but long gradient toward the Rocky Mountains.

Monsoon fog occurs along some coasts during the summer (wet) MONSOON. It is caused by ADVECTION when monsoon winds carry warm, very moist air across a cold land surface.

Radiation fog forms on clear nights when the relative humidity is fairly high. During the day, the ground absorbs heat from the Sun and warms. At night, it radiates its heat into the sky and because there is no cloud to absorb the radiated heat and warm the air below it, the ground cools sharply. Air adjacent to the ground is cooled by contact with it, and its temperature falls to below the dew point temperature. Water vapor then condenses and fog forms. If the air is still, the fog usually forms a very shallow layer—sometimes so shallow it reaches only to about the knees of people walking through it. If there is a slight breeze, turbulence will carry the fog and the cold air to a greater height and the fog layer may extend to a height of up to about 100 feet (30 m).

The layer of cold, dense air containing the fog lies beneath warmer, less dense air. This prevents the fog from rising. If the ground is sloping, the fog will tend to flow downhill and accumulate in valleys. The following morning, the Sun warms the ground. This warms the air in contact with the ground, and the water droplets making up the fog begin to evaporate. As the ground continues to warm, air warmed by it is carried upward by convection, evaporating more of the fog. The fog clears in this way, from the bottom up, sometimes until all that remains is a layer of white cloud. This gives the impression that the fog is lifting, although that is not what is happening. The process is often described as "burning off," which is rather more accurate.

Early morning radiation fog on I-95 in North Florida ***(Ralph F. Kresge, Historic NWS Collection)***

Steam fog is thin, wispy fog that forms when cold air crosses a water surface that is warmer. It is often seen over lakes in winter. Because the air is cold, it contains less water vapor than it would if its temperature were the same as that of the water. In the layer of air that is immediately adjacent to the water surface and is warmed by it, the water-vapor content is lower than is needed to produce saturation. Evaporation is intense and moist air rises by convection from the warm boundary layer. In the colder air above, the relative humidity of the rising air very quickly reaches 100 percent, and the water vapor condenses again to form the fine droplets of fog. The fog looks like steam, and it forms in the same way as the steam in a bathroom that appears when a hot bath or shower is run when the bathroom is cold and its air temperature is low.

Valley fog is a type of radiation fog that forms in the bottom of valleys. Valleys are especially prone to fogs of this kind, because at night, as the hillsides cool by radiating the warmth they absorbed during the day, air chilled by contact with the cold ground sinks to the valley floor. Valley fog often takes a long time to clear in the morning, because it reflects much of the sunshine (*see* ALBEDO) and although the fog droplets are warmed by the Sun they also lose heat as infrared radiation (*see* SOLAR SPECTRUM). The fog blanket slows the rate at which the ground warms, and so the low-lying air remains saturated.

fog dispersal The deliberate clearance of FOG in order to improve the horizontal VISIBILITY sufficiently to permit aircraft and vehicles to maneuver on the ground and vessels to move safely in coastal waters and harbors. The first attempts to disperse fog were made during World War II and were code-named Fog Investigation Dispersal Operations (FIDO). Since then several other methods have been developed. Which of these is appropriate in a particular situation depends on the type of fog that is to be dispersed, and for this purpose fogs are classified not by the manner of their formation, but by their temperature. Warm fogs consist of water droplets all of which are liquid and warmer than 32°F (0°C). Supercooled fogs contain a mixture of supercooled liquid droplets (*see* SUPERCOOLING) and ICE CRYSTALS and the temperature is between 32°F and -22°F (between 0°C and -30°C). Ice fog consists only of ice crystals and its temperature is below -22°F (-30°C).

Warm fog can be dispersed by heating, mechanical mixing, or seeding with particles. Jet engines sited beside an airfield runway and running at full power will disperse fog over the runway by heating it directly. This raises the dew point temperature (*see* DEW), causing water droplets to evaporate. The method works, but it is costly.

The relative HUMIDITY may also be reduced if dry, warm air can be mixed with the saturated air of the fog. There is usually suitable air above the fog, and all that is needed to achieve thorough mixing is a large fan located above the fog and directed downward. The downwash from a helicopter hovering above the fog works well. Its disadvantage is that a single helicopter can clear fog from only a very local area.

Hygroscopic particles—particles such as salt crystals that have a strong affinity for water—will also disperse fog. The particles must be of the right size. If they are too small, they remain suspended in the air and reduce visibility even more. If they are too big, they simply fall to the ground without having any useful effect. Particles of the right size are scattered into the fog upwind of the area that is to be cleared. Water condenses onto them, forming droplets that are heavy enough to fall to the ground. This removes moisture from the air, allowing many more droplets to evaporate. Within about 10 minutes, a fog-free area is drifting downwind.

Supercooled fog is cleared by a technique that exploits the difference in SATURATION VAPOR PRESSURE over ice and over water. The pressure is slightly lower over an ice surface, which means that if ice crystals and supercooled water droplets occur together water will evaporate from the droplets and freeze onto the ice crystals, so the ice crystals grow at the expense of the droplets. Fog dispersal therefore encourages this process so the crystals turn into SNOWFLAKES and fall to the ground.

Snowflake formation is achieved by seeding the cloud with particles that will act as FREEZING NUCLEI. DRY ICE (solid CARBON DIOXIDE) and liquid propane are commonly used. Dry ice is released from an aircraft above the fog and propane is sprayed from the ground. Dry ice particles readily act as freezing nuclei. Propane droplets rapidly expand and vaporize. This chills the air around them, causing water to freeze and form ice crystals onto which more water will freeze.

Ice fog is difficult to disperse, and at present there is no practical method for doing so. It may be possible to inhibit fog formation by reducing the temperature of the spray of water droplets that causes it. This would reduce the rate of evaporation and, therefore the rate at which ice crystals form by deposition.

Fog Investigation Dispersal Operation (FIDO) was a method devised during World War II to clear fog from military airfields. In the days before pilots could be "talked down" by a ground controller observing their glide paths by means of RADAR (*see* FLYING CONDITIONS), aircraft could take off in fog, using their own instruments for guidance, provided their crews could see well enough to taxi to the runway. If fog enveloped the airfield while they were away, however, they could not return. The aircraft had to be diverted to an alternative airfield (called an alternate) that was fog-free, then brought back to their home base when the weather improved.

FIDO employed perforated metal pipes that were laid on either side of the runway. Gasoline vapor was pumped through the pipes and ignited at the perforations (by an airman with a torch!). The result was a fierce heat that raised the dew point temperature, causing the fog to evaporate. The system remained in operation for about 2.5 years, during which time it allowed 2,500 aircraft to land and consumed about 112,000 tons (102,000 tonnes) of gasoline to do so—almost 45 tons (41 tonnes) of fuel for each landing.

föhn winds Warm, dry winds that occur on the northern side of the European Alps, most commonly in spring. They are of the same type as the North American chinook wind (*see* LOCAL WINDS), and they also occur on the eastern side of the New Zealand Alps and on the leeward side of the mountains of the Caucasus and in Central Asia. At Tashkent, Uzbekistan, a föhn wind can rapidly raise the temperature from about freezing to 70°F (21°C).

A fully developed föhn wind shows as a characteristic shape in the isobars (*see* ISO-) on a synoptic chart (*see* WEATHER MAP). There is a RIDGE on the windward side of the mountains and a föhn trough on the LEE side, producing a pattern of isobars that are reminiscent of a nose. The pattern is known as a föhn nose.

There are two ways that a wind of the föhn type may develop. Both require that the mountains are high and that the range extends a long way across the path of the moving air. The range must also be wide, so the air has to travel a considerable distance at high level.

The first and simplest mechanism involves the forced ascent and descent of air as it crosses a mountain range. As the air rises on the windward side of the range it cools, first at the dry adiabatic LAPSE RATE (DALR) and above the lifting condensation level (*see* CONDENSATION) at the saturated adiabatic lapse rate (SALR). Cloud forms, PRECIPITATION falls, and by the time the air reaches the top of the mountains it is fairly dry. The air then flows down the leeward side. As it does so it warms at the DALR and at the same time its relative HUMIDITY and absolute humidity decrease. Because the SALR is lower than the DALR, this mechanism will warm the air by about 2°F for every 1,000 feet (4°C per km) that the air is made to climb and descend. If the mountains rise 8,000 feet above the plain, for example, then air that starts its ascent at, say, 30°F (-1°C) should be at about 46°F (8°C) by the time it reaches the plain on the far side.

This is certainly what happens in some cases, but it is not the whole story, because sometimes there is no precipitation on the windward side. In this case there is a temperature INVERSION at the level of the mountaintops. Air approaching the mountain below the level of the inversion is unable to rise because of the inversion. This prevents the formation of cloud and precipitation. Air approaching the mountain above the inversion level is not barred in this way, however. It crosses the mountains, then slides over the top and down the lee side, warming adiabatically as it does so. The result is a warm, dry, föhn wind, but with dry air on the windward side of the mountains.

When a föhn wind is the result of BLOCKING on the windward side by an inversion at the level of the mountain summit, the stage that has been reached in the development of the wind is known as the föhn phase. There are three phases. In the first, a subsidence inversion (*see* INVERSION), often producing anticyclonic gloom (*see* ANTICYCLONE), separates cold air at the surface from warmer air aloft. In the second, SUBSIDENCE increases the surface AIR PRESSURE on the lee side of the mountain and cold air is pushed away. In the third, the föhn wall (*see* CLOUD TYPES) forms and the föhn wind blows down the mountainside and across the plain.

Adiabatic cooling and warming explains the temperature of the subsiding air, but it does not explain the speed of föhn winds, which can reach gale force. The wind is an effect of the gravity waves (*see* ATMOSPHERIC WAVES) that develop as air is forced to rise, then sinks by gravity, overshoots, and rises again. Where the moving air passes through a constricted vertical space, close to the mountaintops and again as it sinks close to the ground on the lee side, wind speed increases. In the intervening regions, where the air is not constricted in this way, wind speed slows.

Warm air that is carried down a mountainside by a föhn wind is known as föhn air. The boundary between föhn air and the cold air adjacent to it is called the föhn pause. A low-lying area on the lee side of a mountain that is affected by a föhn wind is called a föhn island. Adjacent areas remain under the influence of the cold air, so the area that lies beneath föhn air is like an island of warm air in a sea of cold air. The föhn period is the length of time during which a specified place lies beneath föhn air.

A temporary cessation in exposure to föhn air can occur when cold air intrudes and lifts the warm air clear of the ground. This is also called a föhn pause, and its effect can be dramatic, especially when it is repeated at fairly frequent intervals. Rain, falling from clouds at a higher level, is warmed as it passes through the layer of föhn air and reaches the ground as warm rain. As the cold air intrudes, the temperature drops sharply. The ground surface temperature falls to below freezing, so the layer of water left by the warm rain freezes. Repeated changes from warm to cold air allow a thick layer of ice to accumulate.

Forecast Systems Laboratory (FSL) The former name of the GLOBAL SYSTEMS DIVISION (GSD) of the Earth System Research Laboratory (ESRL) of the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA). The name was changed on October 1, 2005.

freezing The change of phase from liquid to solid, and in the case of water the change from liquid to ice. Change in the opposite direction, from solid to liquid, is called melting. A day on which the air temperature does not rise above freezing and when ice on the surface of water does not thaw is called an ice day.

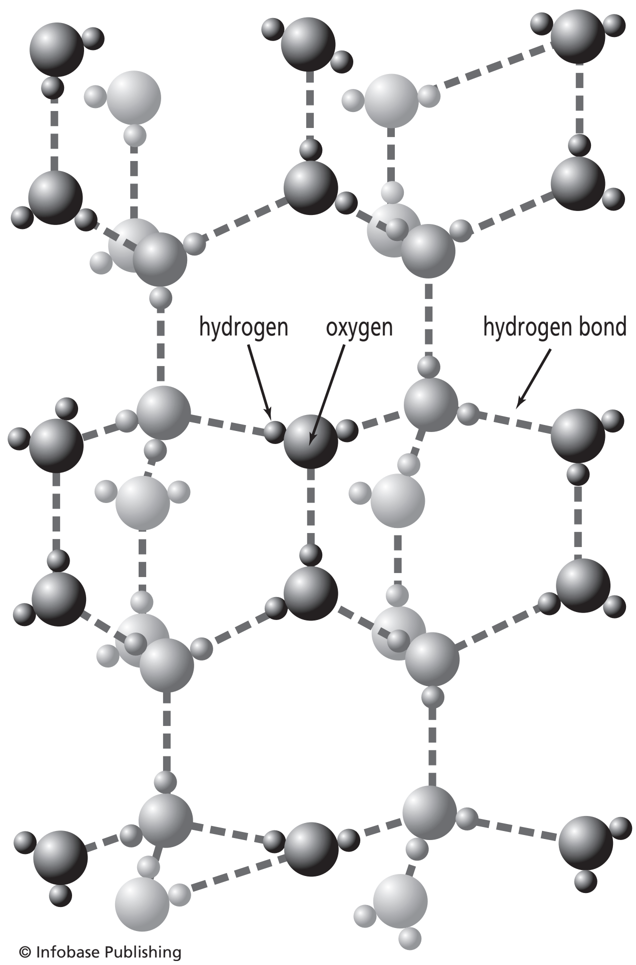
Like all molecules, water molecules move. Their freedom to move depends on the amount of energy they possess. It is the vigor with which they move that defines the quality we measure as TEMPERATURE. The less energy they possess the less vigorously they move, and the less vigorously they move the lower is their temperature. As molecules cool, therefore, they move with less and less vigor. In liquid water the molecules form small groups that slide over and past each other quite freely, but as the temperature falls, the water molecules lose energy and move more slowly. Molecules pack together more closely, and the water contracts to occupy a smaller volume.

Then, as the temperature approaches a critical value, the freezing point, the molecules rearrange themselves. Water molecules are linked to one another by hydrogen bonds (*see* CHEMICAL BONDS). In the liquid phase these are constantly breaking and re-forming, because the individual molecules have sufficient energy to break free from them, but insufficient energy to remain free. As water turns into ice, the molecules no longer have enough energy to break free and the hydrogen bonds hold them together. The molecules lock together. This requires less energy than they possessed when they moved freely and the surplus energy is released as LATENT HEAT. Ice molecules are not motionless, but they are no longer able to move freely. Their movement is restricted to vibrating about a fixed point.

As they form ice, each molecule forms hydrogen bonds with four neighboring molecules. This produces a very open structure with an empty space at the center of each ICE CRYSTAL. Consequently, as water freezes it also expands and it does so with sufficient force to fracture metal pipes.

Ice consists of water molecules that are arranged in a regular, repeating pattern called a lattice. At the ice surface, however, there are fewer hydrogen bonds to hold the molecules in place (because on one side the surface molecules are exposed to air). The lattice is disordered where surface molecules project into the air. These molecules vibrate more vigorously than those in the solid lattice of the interior and, at a temperature well below freezing, the surface layer of the ice, just a few molecules thick, is able to move as though it were a liquid. This is called surface melting, and scientists believe it explains why ice is slippery—which is the characteristic of ice that makes skating possible.

The melting point is the temperature at which the solid and liquid phases of a substance are in equilib-



The arrangement of water molecules in ice. Each molecule is linked by hydrogen bonds to four neighboring molecules (not all the bonds are shown in this two-dimensional representation of a three-dimensional structure). The result is an ordered, but very open structure.

rium at a given pressure. The melting point of pure water at the standard sea-level pressure of 1,013.25 mb (760 mm or 29.92 inches of mercury) is 32°F (0°C, 273.15K). When water melts, 80 calories per gram (334 joules per gram) of latent heat is absorbed.

Further Reading

Wettlaufer, John S. and J. Greg Dash. "Melting Below Zero." *Scientific American,* February 2000, 34–37.

freezing level The lowest height above sea level at which the air temperature is 32°F (0°C). This varies from place to place and from time to time, but if all the points where the temperature is at freezing are joined to form an imaginary surface, the spatial variations will appear on this constant-temperature surface, like the hills and valleys of a landscape.

The height of the freezing level is determined by the environmental LAPSE RATE. Suppose the temperature at sea level is 75°F (24°C), the tropopause (*see* ATMOSPHERIC STRUCTURE) is at a height of 46,000 feet (15 km), and the temperature at the tropopause is -76°F (-60°C). Therefore, the temperature decreases from 75°F (24°C) to -76°F (-60°C) over a vertical distance of 46,000 feet (15 km), which is a decrease, or lapse rate, of 3.3°F per 1,000 feet (5.6°C per km). Assuming this lapse rate remains constant through the troposphere (in reality it may not), the air temperature will be 32°F (0°C) at a little over 13,000 feet (about 4 km).

freezing nuclei Small particles onto which supercooled water droplets (*see* SUPERCOOLING) will freeze. They are crystals with shapes similar to that of an ICE CRYSTAL, and actual ice crystals formed by DEPOSITION onto sublimation nuclei become freezing nuclei, suitable for further ice formation. Splinters of ice that break away from aggregations of crystals as these are moved violently by vertical air currents also act as freezing nuclei.

Most of the mineral particles onto which water freezes are believed to be fine soil particles, and a small proportion may be meteoric (entering from space) or injected by volcanic eruptions. Freezing nuclei are much less numerous than CLOUD CONDENSATION NUCLEI, there seldom being more than about three freezing nuclei per cubic foot ($100/m^3$) of air.

Depending on their crystal structure, different freezing nuclei trigger the formation of ice at different temperatures. Ice starts to form on kaolinite particles, for example, at 16°F (-9°C), and once ice is forming it will continue to do so on particles at temperatures up to 25°F (4°C). Kaolinite is a widespread clay mineral that occurs in many soils. Most freezing nuclei do not become active until the temperature falls to about 14°F (-10°C), however, so clouds above this temperature consist predominantly of supercooled water droplets. Liquid droplets and ICE CRYSTALS occur in approximately equal numbers at temperatures between 14°F (-10°C) and -4°F (-20°C). Below -4°F (-20°C) ice crystals predominate.

The freezing of supercooled WATER droplets onto freezing nuclei is called heterogeneous nucleation. Heterogeneous (from the Greek *heteros* meaning "other") refers to the fact that two different substances—a solid particle and water—are involved. Homogeneous nucleation is the spontaneous freezing of supercooled water droplets that occurs at very low temperatures in the absence of freezing nuclei. The process is said to be homogeneous (from the Greek *homos* meaning "same") because only one substance, water, is involved.

freshwater WATER that contains very little salt, usually defined as less than 0.03 percent by volume. When water evaporates or freezes, it is only water molecules that enter the air as WATER VAPOR or form ICE CRYSTALS. Molecules of any substances that were mixed with or dissolved in the water remain behind. Consequently, water vapor that condenses to form clouds is fresh, and PRECIPITATION consists of only freshwater (although substances present in the air may dissolve in atmospheric water droplets). Similarly, ice, including sea ice and ICEBERGS, is made from freshwater, although small amounts of salt water may be held between ice crystals.

friction The force that resists the motion of a solid body or of a fluid in contact with a surface that is either stationary or moving at a different speed or in a different direction. Wind that blows over a surface is slowed by friction with the surface, because the surface exerts a force acting in the opposite direction to that of the wind. The extent to which it is retarded depends on the AERODYNAMIC ROUGHNESS of the surface and the square of the speed of the wind. This type of frictional effect is called DRAG.

According to Newton's third LAW OF MOTION, the force with which a surface retards the wind must be equal to a force exerted by the wind in the opposite direction. Since this force is proportional to the square of the wind speed, a wind blowing at 120 MPH (193 km/h) exerts 100 times more pressure on objects in its path than a wind blowing at 12 MPH (19 km/h), not 10 times more. The force the wind exerts on a surface is called the surface shearing stress (*see* SHEAR).

Friction transfers momentum from the wind to the surfaces on which it exerts pressure. Mountain ranges do not bend with the wind, but westerly winds, blowing from west to east, accelerate the rotation of the Earth. Fortunately, the westerly winds are balanced by winds blowing in the opposite direction. Nevertheless, the rotational speed of the Earth does vary by a very small amount due to the changing winds.

Wind over the ocean causes waves. This transfers energy from the wind to the water. Friction between layers of water below the surface produce an EKMAN SPIRAL, and this in turn causes UPWELLING. Friction with a smooth surface also produces an Ekman spiral in the air.

Surface friction affects air in the PLANETARY BOUNDARY LAYER. Beyond the boundary layer, friction also occurs between layers of air moving in different directions. This arises mainly from TURBULENT FLOW, and it occurs in EDDIES that turbulence produces. Its magnitude is proportional to the VISCOSITY of the air.

front The boundary between two AIR MASSES that possess different characteristics. Their different characteristics (of TEMPERATURE, HUMIDITY, and AIR PRESSURE) mean that the air in one air mass is denser (*see* DENSITY) than the air in the other air mass. This limits the extent to which air from the two masses can mix across the boundary, because the denser air tends to push beneath the less dense air, pushing it upward. Overrunning is the term describing the situation in which warm air rides up a frontal surface, moving over the cold air that is beneath the front. The study of data recorded on weather charts in order to identify the boundaries between adjacent air masses and to mark the fronts separating them is called frontal analysis.

Fronts separate masses of air at different temperatures. If the fronts move across the surface, they are named "warm" or "cold" in respect of the air behind them. The designation is relative. To put it another way, fronts are identified by the change in temperature associated with them. A cold front advances with the warm air ahead of the cold air. Air behind a cold front is cooler than the air ahead of the front, so the air temperature falls as the front passes, but "cold" implies no particular temperature. The cold air, being denser, forms a wedge beneath the warm air, lifting it. A warm front marks the boundary between cold air and advancing warm air. Air behind a warm front is warmer than the air ahead of the front.

A collision of air masses, where warm and cold air meet. Fronts are rarely so clearly visible as this one. ***(Historic NWS Collection)***

A boundary, resembling a small front and called a pseudofront, sometimes develops between air that is cooled by rain falling through a large cumulonimbus cloud and the warmer air adjacent to it.

The boundary that is formed when cool, maritime air advances beneath warmer air over land, producing a sea or lake breeze (*see* LAND AND SEA BREEZES) is called a sea-breeze front or lake-breeze front. Fronts of this type occur in summer along seacoasts and the shores of large lakes.

Certain fronts separating tropical and polar air result from the GENERAL CIRCULATION of the atmosphere. The arctic front exists for most of the time in northern latitudes between arctic air and more temperate air masses to the south. It extends across the whole of Eurasia and lies close to the Arctic Circle (*see* AXIAL TILT).

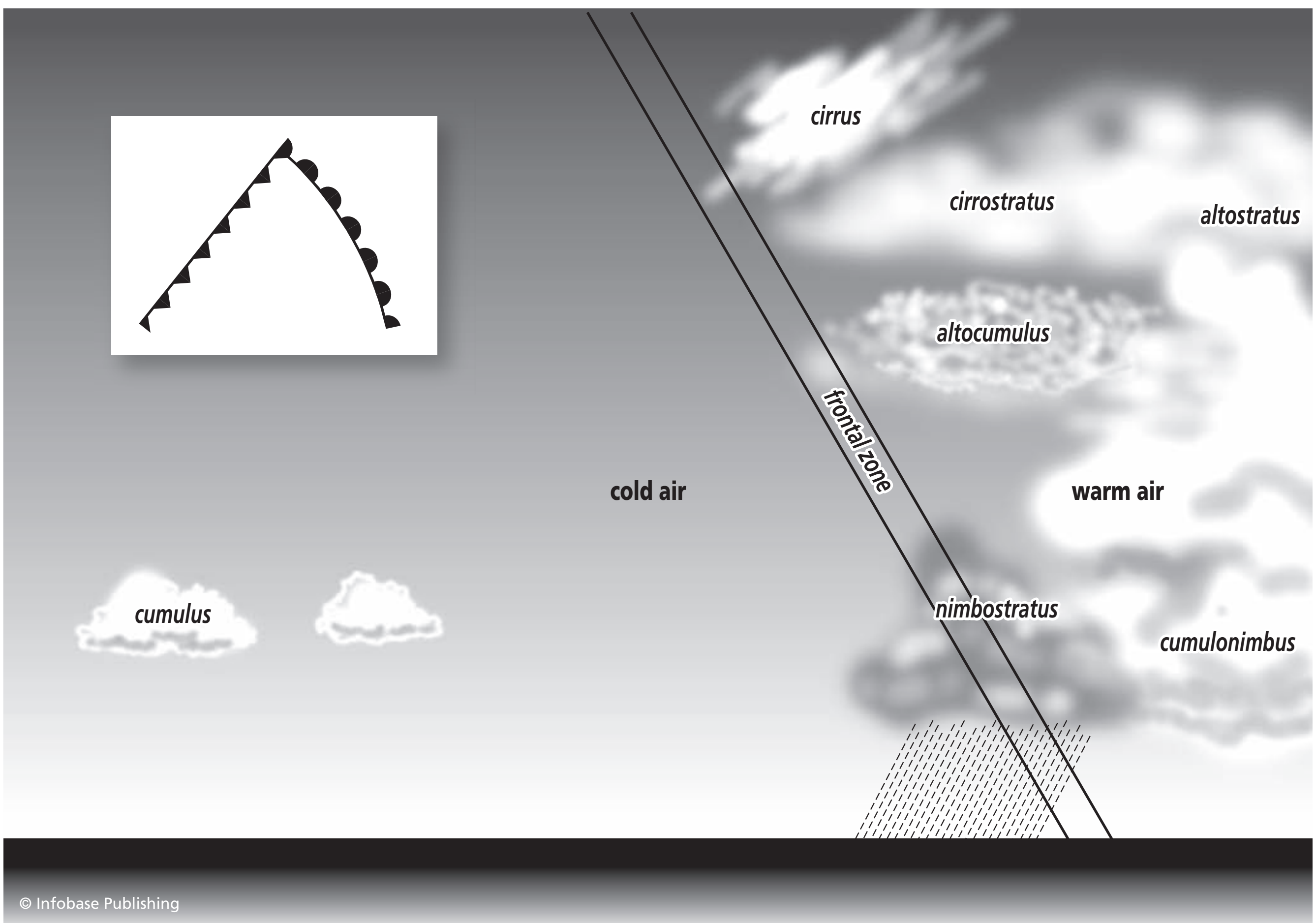
A front that advances southward across North America and has arctic air behind it is also known as an arctic front. It usually brings bitterly cold weather.

A third type of arctic front forms in winter over snow and ice when the wind is weak or blows parallel to the edge of the SEA ICE. This situation produces a large difference in temperature between air that is chilled by its contact with the snow and ice and air that is warmed by its contact with the sea. The resulting front is shallow, but it can trigger the formation of a POLAR LOW.

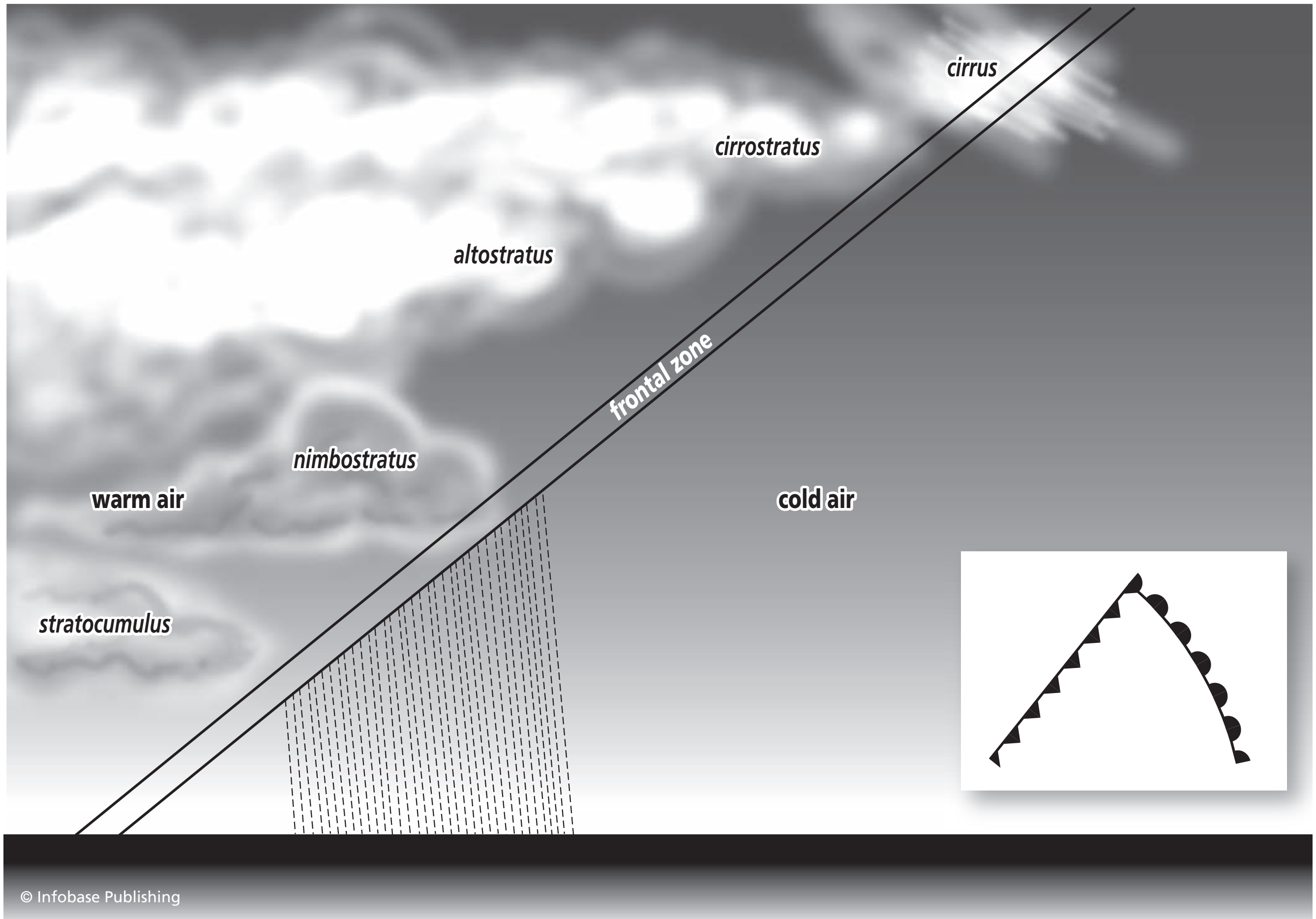
The Antarctic front marks the boundary between arctic air and polar air over the Southern Ocean. The Antarctic front is almost permanent and almost continuous around the continent of Antarctica. In summer the front lies close to the coast of Antarctica, separating continental arctic air (cA) from maritime polar air (mP). In winter the front moves farther north over the Ross Sea, where it separates maritime arctic (mA) from mP air, but the front remains in the same position around the remainder of the continent.

The polar front is located in middle latitudes and marks the boundary between polar air on the poleward side and tropical air on the equatorial side. This is also the boundary between the direct polar cell and indirect mid-latitude cell in the three-cell model of the general circulation of the atmosphere. Prevailing winds (*see* WIND SYSTEMS) are easterly in the polar air and westerly in the tropical air, and air masses travel in the same direction as the winds. The polar front extends from the surface to the tropopause (*see* ATMOSPHERIC STRUCTURE), where it generates the polar front JET STREAM.

Polar front theory is an explanation for the way CYCLONES form and cross the middle latitudes. The theory was devised by Vilhelm Bjerknes (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) and his colleagues at the BERGEN GEOPHYSICAL INSTITUTE in Norway, and was first described by Jacob Bjerknes in an article titled "On the



In a cold front, cold air lies behind the front and warm air rises ahead of it, producing stratiform cloud. A cold front is shown on a weather map as a line with a row of triangles. The side of the front with the triangles indicates the direction the front is advancing.



A warm front has warmer air behind it. Warm fronts are associated with stratiform cloud and are shown on weather maps as lines with semicircles along the leading edge, indicating the direction the front is moving.

Structure of Moving Cyclones" that was published in 1919. Using data obtained from balloon observations, the Bergen team proposed the existence of the polar front. At the surface, they found that the polar front is often broken into sections that are separated by regions in which the temperature gradient is much shallower than it is in the frontal zone. Waves develop in the sections of frontal zone, and the team coined the names warm front and cold front to distinguish the two types of front that enclose the frontal wave (*see* FRONTOGENESIS).

In 1922, Bjerknes and Halvor Solberg published another article, "The Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation" (in *Geofisiske Publikasjoner,* Oslo), in which they drew together their ideas about the polar front and the dynamics of cyclone formation. The combined theories described the formation and movement of mid-latitude frontal cyclones in a context of the transport of heat away from the equator and the general circulation of the atmosphere. The polar-front theory soon became, and has remained, a central feature of the science of meteorology, although several of its details have been revised in the light of more recent discoveries. It is now known to be relevant to the formation of frontal cyclones along other fronts, as well as along the polar front.

A complete system of warm, cold, and occluded fronts (*see* OCCLUSION) as these are shown on a WEATHER MAP is known as a frontal system. The front that is the first to form in a frontal system is called the primary front. One or more secondary fronts then develop from it along the frontal wave. A secondary cold front can also develop in the cold air behind a frontal cyclone when the horizontal temperature gradient is so strong that the cold air starts to separate into two distinct masses, one of which is colder than the other.

The way air moves, cloud forms, and PRECIPITATION develops in a frontal system is called the frontal structure. At first, before a frontal wave starts to appear, air is rising throughout the troposphere. This generates stratiform cloud along the front. Air converges to replace the rising air, and planetary VORTICITY causes it to start rotating cyclonically (*see* CYCLONE). This increases the temperature gradients, because warm air is being carried toward the pole on one side of the circulation and cold air is being carried toward the equator on the other side. As the frontal wave begins to develop, precipitation starts falling over a large area. There is then much middle and high cloud, including some cirrostratus (*see* CLOUD TYPES). Air at high level rotates anticyclonically (*see* ANTICYCLONE), because of high-level divergence (*see* STREAMLINE). Divergence then starts removing air at high level faster than it can be replaced by convergence at low level and the surface air pressure falls sharply. Nimbostratus covers a large part of the sky in the warm and cold frontal zones, producing heavy precipitation, and there is altostratus and cirrostratus above it. As the fronts occlude, the center of low pressure moves further toward the pole. Then, as the fronts dissipate, the temperature gradient slackens, the clouds start to clear, and precipitation ceases.

The dissolution and disappearance of a weather front that occurs when there is no longer any difference in the characteristics of two adjacent air masses is called frontolysis or frontal decay. The disappearance of a front in what had been an active frontal system is often marked by occlusion, as warm air is lifted clear of the surface and gradually absorbed into the surrounding air. It can also happen when two air masses remain stationary for a long time over a similar surface and both become modified by contact with that surface until they are both at the same temperature, pressure, and humidity. If the air masses are both moving, they can also acquire similar characteristics if they spend a long time moving side by side and at the same speed over a similar surface, or if one travels behind the other at the same speed and along the same track.

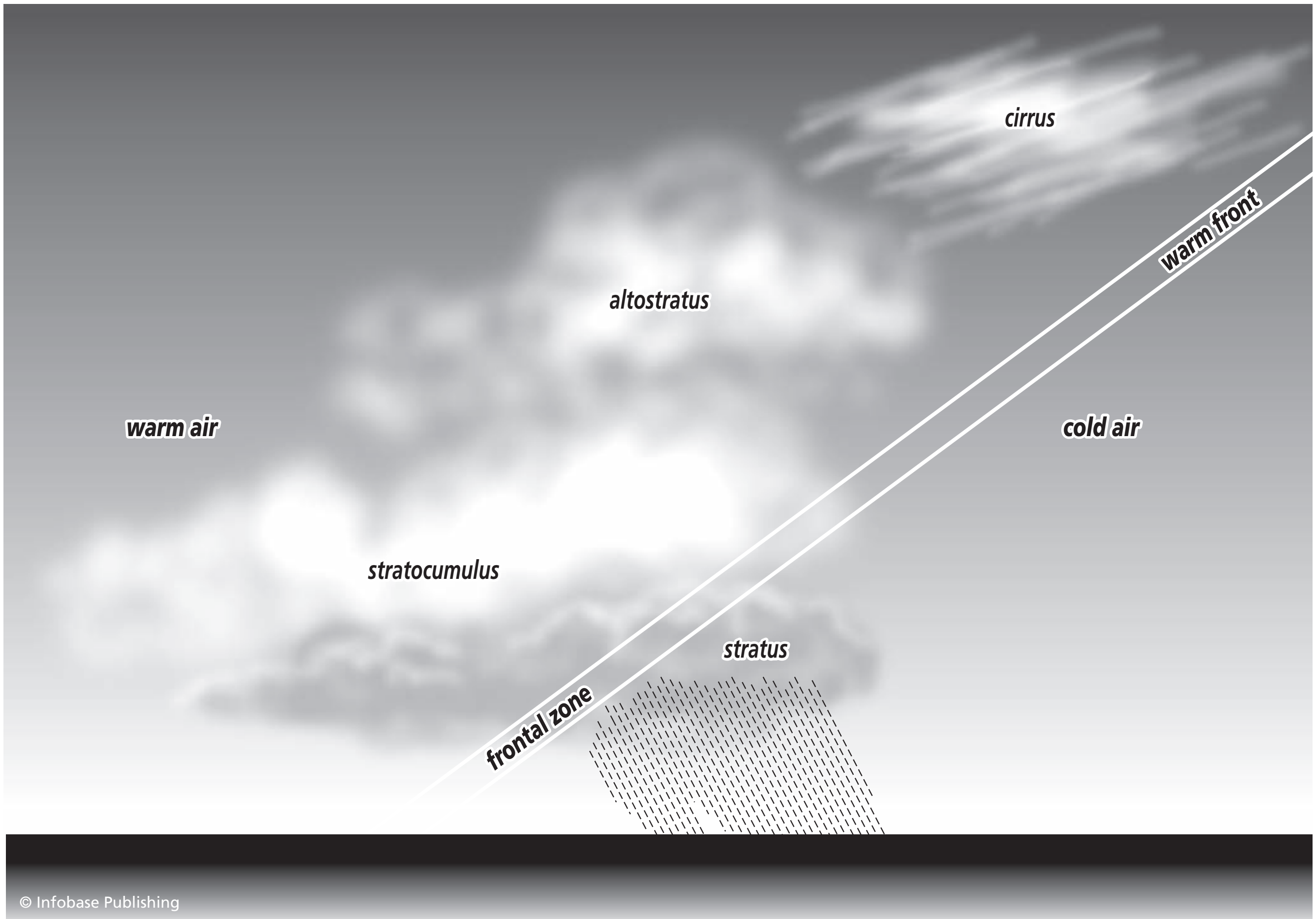
A frontal contour is a line that marks the intersection between a front and a surface. WEATHER MAPS show frontal contours with respect to the Earth's surface and the contours mark the location of the fronts with respect to the surface. Frontal contours can also be drawn for atmospheric constant-pressure surfaces (*see* ISO-). A warm front is marked on a weather map as a line with a row of semicircles along its leading edge. If the map is in color, the line and semicircles are in red. A cold front is indicated by a line with triangles along its leading edge. If the map is in color, the line and triangles are in blue. The representation of a front on a weather map as two parallel lines, rather than as a single line is called a frontal strip. It shows that the front is a band of transition between two air masses, rather than the abrupt change suggested by a single line. Despite its ability to show the location of the boundaries of the frontal zone, fronts are rarely depicted as frontal strips.

A diagram that shows a vertical cross section through a front, sometimes with the clouds that are associated with the front at different heights, is called a frontal profile. A weather front that is present in the upper air, but that does not extend to the surface, is called an upper front.

Fronts do not rise vertically. The gradient of a warm or cold front, which is measured either as the angle between the front and the Earth's surface or as the ratio of vertical-to-horizontal distance, is known as the frontal slope. A warm front has an average slope of between 0.5° and 1°, or a gradient between about 1:115 and 1:57. A cold front slopes much more steeply, at about 2°, or about 1:30. When the cold front reaches a point on the surface, the upper edge of the front is about 185 miles (300 km) away. Cirrus is often the cloud that forms at the top of a warm front, close to the tropopause. When cirrus associated with a warm front is overhead, the point where the front is at the surface is about 350–715 miles (570–1,150 km) away.

The frontal zone is the region of a front where the temperature gradient is strongest. Because fronts slope at a very shallow gradient, the position of the frontal zone in the upper troposphere is directly above a surface position that is a long distance from its position at the surface. As a frontal wave develops, the frontal zones become more sharply defined and the temperature gradient can reach about 14.5°F per 100 miles (5°C per 100 km). The frontal zone of both cold and warm fronts is 60–120 miles (100–200 km) wide.

The tropical air on the low-latitude side of the polar front is drawn into higher latitudes by the frontal wave. This constitutes the air of the warm sector, and in winter it brings a marked rise in temperature. The warm sector is the region between the warm and cold fronts of a frontal system, containing the wedge of warm air inside the frontal wave. Stratiform cloud often forms in the warm air behind the warm front, and in winter advection FOG may develop where warm, moist air crosses a cold surface. Elsewhere, cloud in the warm sector is often broken, although nimbostratus and cumulonimbus may develop along a cold ana-front.

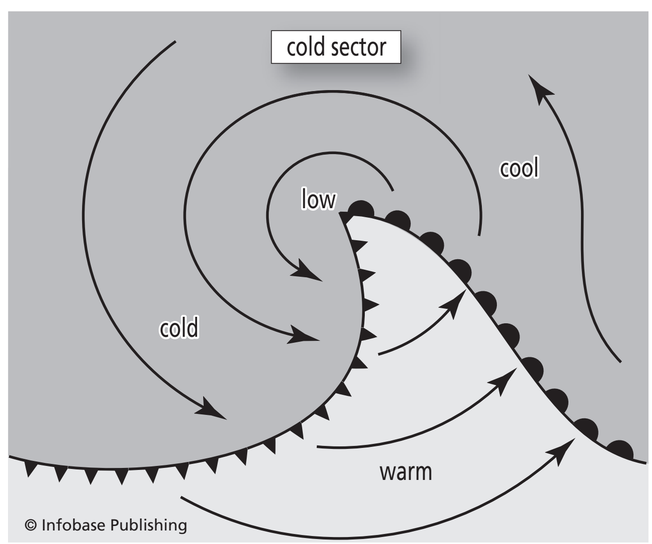


A frontal profile is a cross-sectional view of a front, together with the cloud and precipitation associated with it.

The cold air that partly surrounds the warm sector during the development of a frontal system makes up the cold sector. Once the system reaches the occlusion stage and all of the air in the warm sector is lifted above the surface, the whole of the surface air makes up the cold sector.

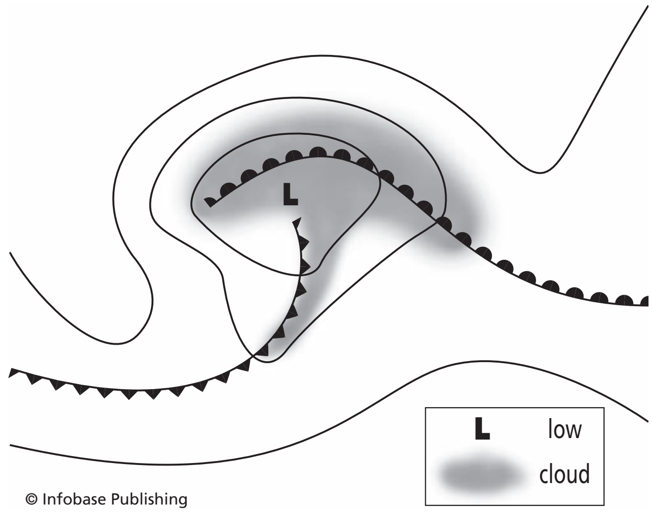
The movement of a front over a point on the surface is known as the frontal passage. This is not an instantaneous event. A warm front travels at an average 15 MPH (24 km/h) and a cold front at an average 22 MPH (35 km/h). It may take 4–8 hours for a warm front to pass and 2.75–5.5 hours for a cold front.

If the air on either side of a front is moving approximately parallel to the front, there is no air movement to carry one air mass forward against the other. Consequently, the surface position of the front, does not move, or moves erratically and slowly. It is then known as a stationary front, and it may remain in the same



As the cold front (on the left) advances into the warm air, cold air surrounds the wedge of warm air, forming a cold sector.

A wall of cloud associated with a fast-moving cold front *(Historic NWS Collection)*



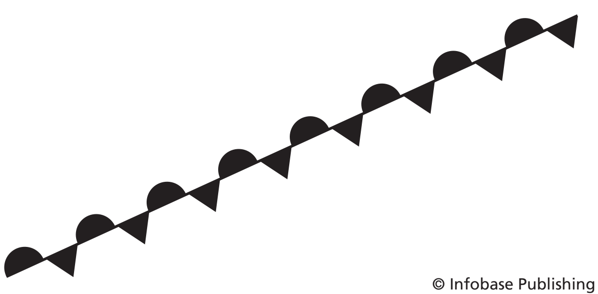
In a back-bent warm front, the cold and warm fronts have separated, and the warm front is bent back around the low-pressure center.

position for several days. A stationary front is shown on weather maps as a line with (red) semicircles on one side and (blue) triangles on the other. Stationary fronts may be active or weak. Those that are active produce stratiform cloud with a low base. A front that is moving at less than about 5.75 MPH (9.25 km/h) is called a quasi-stationary front.

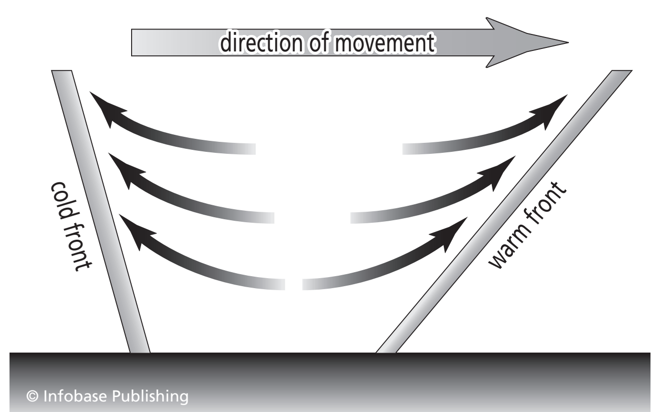
It sometimes happens that a warm front curves around the CYCLONE situated at the point where the warm and cold fronts meet. This is a back-bent warm front, also called a bent-back warm front, and it develops when the cold front separates from the warm front and starts to move at right angles to it, while at the same time the low-pressure center is moving rapidly. The strong winds ahead of the warm front then bend the front around the low center.

The weather associated with a front varies, depending on whether it is an ana-front or a kata-front. An ana-front is a front at which air in the air in the warm sector is rising. As the air rises, it cools adiabatically (*see* ADIABAT) and its water vapor condenses. Consequently, unless the air in the warm sector is unusually dry, ana-fronts are very active. With an ana-front, stratiform cloud occurs all the way to the top of the front, at the tropopause. Cirrus appears overhead about 600 miles (1,000 km) ahead of the point at which the front touches the ground. PRECIPITATION falls throughout a belt about 250 miles (400 km) wide.

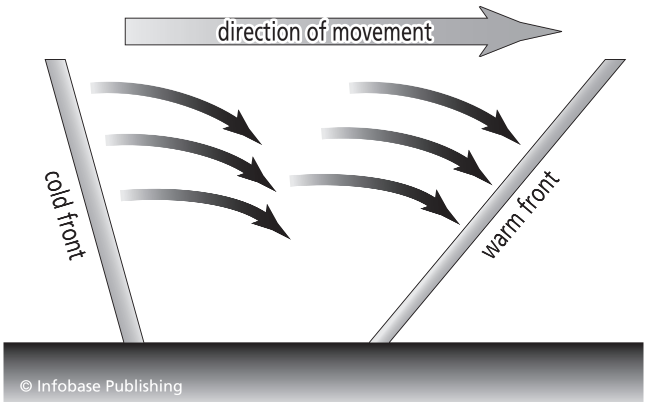
A kata-front is one at which air in the air in the warm sector is subsiding relative to the cold air on



A stationary front is shown on weather maps as a line with semicircles on one side and triangles on the other.



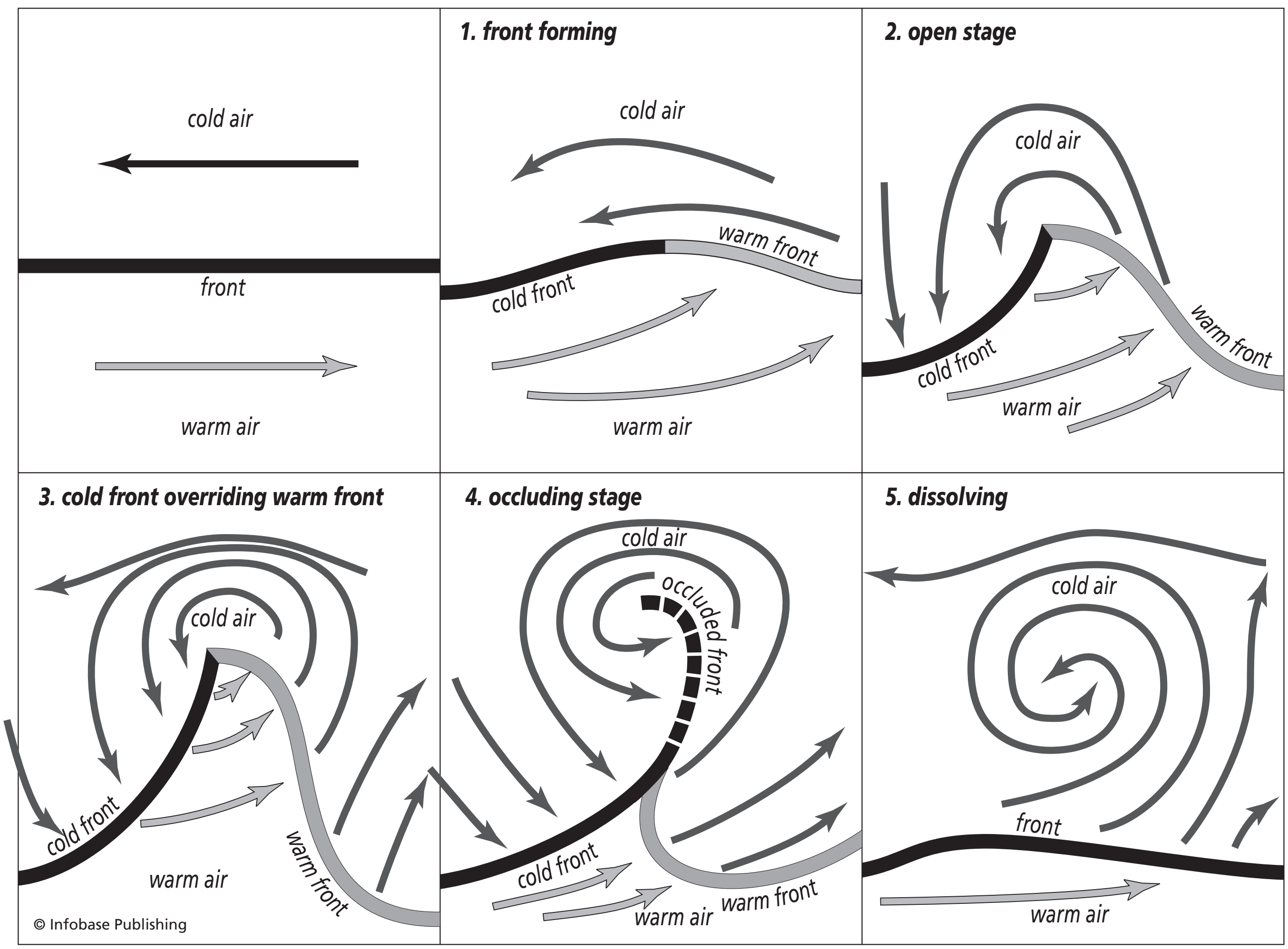
In an ana-front, air rises against the fronts.



At a kata-front, the air is subsiding, producing very stable conditions.

either side of the fronts. Often, warm-sector air is trapped beneath a temperature INVERSION at about 10,000 feet (3 km). Although there is usually a complete cloud cover and cloud is especially thick in the vicinity of the fronts, the vertical extent of the cloud is limited by the inversion. Precipitation at a warm kata-front consists of a belt of drizzle or light rain and that at the cold front consists of showers.

Frontal lifting is the forced ascent of warm air as it rises over an adjacent mass of cold air at a warm front, or as it is undercut by advancing cold air at a cold front. It occurs because warm air is less dense than cold air and air masses (or water masses) of different densities do not mix readily.



A frontal system develops from a frontal wave, in a sequence of events by which an undulation that appears in a front between two air masses grows into a wave, or depression, that occludes and finally dissipates.

The situation in which warm air is rising and cold air subsiding within a frontal zone is described as direct circulation. This is a stage in cyclogenesis (*see* CYCLONE), which is the intensification of the front. At a weakening front the circulation is in the opposite direction, with cold air rising and warm air sinking.

Fronts can be active or inactive. An active front is associated with appreciable amounts of cloud and precipitation. This implies that the relative HUMIDITY is high in the air behind the warm front, so cloud forms as it is forced to rise. If the air in the warm sector is unstable (*see* STABILITY OF AIR) and there is a sharp difference in temperature on either side of the front, a warm front may become extremely active, with cumulus and cumulonimbus cloud accompanied by THUNDERSTORMS. This is uncommon, and warm fronts are usually associated with stratiform cloud. An inactive front, also known as a passive front, has very little cloud or precipitation associated with it. People on the ground may notice its passing only by the change in temperature as one air mass replaces another.

In a weak front, the warm front is overriding a mass of cold air, but behind it the relative humidity of the air is low. As the warm air rises and cools, little or no cloud forms and consequently the front produces no appreciable change in the weather. A weak front may pass unnoticed.

Precipitation often varies in intensity in the area of precipitation ahead of a warm front, the variations forming a pattern of bands. This is known as banded precipitation or rainbands. The bands occur on a small scale and are probably due to local instabilities along the front.

A backdoor cold front is one that develops where the sea-surface temperature is much lower than the air temperature over land. Warm and cold air then become sharply separated. In North America the cold front brings a cold air mass southward along the Atlantic coast toward the south and southwest of the United States. The front arrives from the northeast, rather than from the west or southwest, the direction from which most weather systems arrive. Similar fronts occur along the eastern coasts of continents in the Southern Hemisphere, but there they travel northward.

A tongue-shaped extension of dry air that protrudes into a region of moister air is called a dry tongue.

frontogenesis The formation and subsequent development of a boundary between two AIR MASSES. Such a boundary is known as a weather FRONT, and it exists because air that belongs to one air mass does not mix readily with air belonging to an adjacent mass and possessing substantially different characteristics. The name "front" was introduced during World War 1 by the team of meteorologists at the BERGEN GEOPHYSICAL INSTITUTE led by Vilhelm Bjerknes (*see* APPENDIX I: BIOGRAPHICAL ENTRIES).

Where two air masses meet, there is a boundary between them, about 60–120 miles (100–200 km) wide, across which the TEMPERATURE, pressure, WIND, and HUMIDITY change sharply. Although this makes the boundary seem wide, it is thin enough to be shown on a WEATHER MAP as a single thick line. Air on one side of the boundary is warmer than air on the other side. The warmer air is less dense and at a lower pressure than the cooler air. Convergence (*see* STREAMLINE) into the warmer air and divergence from the cooler air establish winds blowing in opposite directions. The direction of the wind is cyclonic (counterclockwise) around the center of the low-pressure, warmer air and anticyclonic (clockwise) around the center of the high-pressure, cooler air. In the Northern Hemisphere cyclonic circulation is counterclockwise and anticyclonic circulation is clockwise. These directions are reversed in the Southern Hemisphere.

Usually both air masses are moving, but not at the same speed. As one advances against the other, the warmer air, which is less dense, rises over the cooler, denser air. The boundary, or front, does not rise vertically, therefore, but along a shallow frontal slope (*see* FRONT). Warm air cools adiabatically (*see* ADIABAT) as it rises over the cooler air. If it is moist, its water vapor condenses to form cloud that may produce PRECIPITATION. Sometimes cold air advances so fast against warm air that it triggers enough instability (*see* STABILITY OF AIR) to produce a SQUALL line.

A front at which air is rising is called an ana-front, but it can also happen that air subsides down a front. One where this is happening is called a kata-front. The two types of front produce quite different clouds and weather. An ana-front produces large amounts of cloud, mainly of a stratiform type but sometimes including cumulonimbus near the cold front, and extensive, continuous, and often heavy precipitation. A kata-front often produces a complete cloud cover, with showers at the cold front and a belt of light rain or drizzle at the warm front.

WIND SHEAR on either side of the front causes a wave to develop with air circulating around it cyclonically and warm air projecting into the cold air mass. The center of the cyclonic flow is at the crest of the wave and is also the region of lowest atmospheric pressure. At this stage the boundary has become a frontal wave, or frontal DEPRESSION, and there are two fronts, with a wedge of warm air between them.

Once the frontal wave has formed, the weather system enters its open stage. Cyclonic circulation surrounds the center of an area of low pressure at the crest of the wave. This area constitutes the depression. The system travels with a warm front at the leading edge of the wedge of warm air and a cold front at the trailing edge.

The cold air to the rear of the system travels faster than the warm air, causing the cold front to override the warm front. The tip of the wedge of warm air is lifted clear of the surface by cold air pushing beneath it, and the fronts appear on a weather map as an OCCLUSION. This is the occluding stage in the life cycle of the frontal wave. The cold front continues to advance against the warm front, causing the occluded section of the fronts to grow longer. Eventually, the whole of the wedge of warm air has been lifted clear of the surface.

When all of the warm air has been lifted above the surface, the system dissolves. A section of occluded front survives for a time, but it quickly shortens and then disappears, the occluded fronts disappearing as the warm and cold air mix. With the frontal wave dissipated, the original front reappears as a fairly straight boundary between the two air masses and the stage is set for the cycle to repeat itself.

A frontal cyclone is a region of low atmospheric pressure, around which the air circulation is cyclonic, and that is associated with a frontal system. The term is synonymous with frontal wave, but is sometimes used to distinguish a cyclone of this type from a TROPICAL CYCLONE.

frost A coating of ICE CRYSTALS that forms on solid surfaces. It is most often seen on objects close to ground level, such as plants, parked cars, windshields, and windows. Frost also forms on the surface of fallen snow and in air pockets in the snow. The layer of ice greatly restricts the radiation of heat from the underlying surface and the DEPOSITION of ice or freezing of DEW release LATENT HEAT, warming the air immediately adjacent to the surface. Consequently, frost formation reduces further cooling of the bodies it covers.

The number of degrees Fahrenheit by which the temperature is below freezing is sometimes described informally as the number of degrees of frost. For example, a temperature of 26°F might be described as "six degrees of frost" (32 - 26 = 6). The expression was once widely used in Britain, but its use declined with the adoption of the Celsius TEMPERATURE SCALE in radio and television weather forecasts. A day on which frost occurs is called a frost day.

Air frost is the condition in which the air temperature is below freezing. Unlike ground frost, air frost can cause damage to plants. Ground frost is the condition in which the air temperature is above freezing, but the temperature at ground level is below freezing. This occurs on still, clear nights, when the ground and plant surfaces lose heat by radiation but the air at a higher level remains relatively warm. Extensive cloud cover prevents ground frost by reflecting back the radiated heat, and wind prevents ground frost by constantly mixing the ground-level air with warmer air from above.

A flash frost is one that appears on roads very suddenly soon after dawn. As the Sun begins to rise, frost on roadside vegetation begins to melt and evaporate. This causes a rapid and large increase in the relative HUMIDITY of the air close to ground level. Air next to the road surface is chilled, and ice forms by deposition on the road surface. An ice-free road can be covered by frost within 15 minutes. The flash frost soon disappears as the day advances and the temperature rises, but while it lasts it constitutes a driving hazard.

Hoar frost is the most common type of frost. It forms as a thin layer of white crystals on grass, other herbs, shrubs, trees, spiderwebs, and other exposed surfaces. Hoar frost is seen in the morning after a night in which heat radiated from the surfaces of objects has reduced their temperature to below freezing. Air in the layer immediately adjacent to the cold surfaces has been chilled to below its frost point. The frost point is the temperature at which water vapor turns directly into ice. It means that saturation does not occur until the air is cooled to below freezing. Chilling the air to below its frost point raises its relative humidity to above 100 percent, causing water vapor to change directly to ice by deposition. Hoar frost will also form if the temperature falls below freezing after dew has formed. Frozen or white dew is usually hard, transparent, and with rounded surfaces produced by the shape of the original dewdrops.

Hoar frost encrusting a plant *(John Park, Park's Pics)*

Fern frost forming patterns on the windows of the Clean Air Facility at the South Pole Station, Antarctica, December 1978 *(Commander John Bortniak, NOAA Corps)*

Under different circumstances, frozen dew may form fern frost. This is frost that forms in patterns resembling fern fronds. It is most often seen early in the morning on single-glazed windows in unheated rooms (and is now a much rarer sight than it once was). In the early part of the night water vapor condenses onto the cold window from the warm, moist air indoors. As the outside temperature falls, the temperature of the window drops below freezing. The water droplets on the window are also chilled to below freezing but remain liquid (*see* SUPERCOOLING). Eventually, ice crystals start to form between the water droplets. The supercooled water freezes onto the crystals, and a chain reaction occurs in which the ice grows rapidly to cover a large area with the fern pattern. Large supercooled droplets do not produce fern frost. Being larger, they freeze more slowly and form a layer of clear, unpatterned ice.

Rime frost edging the leaves of crape myrtle *(Lagerstroemia indica) (John Park, Park's Pics)*

Rime frost is a layer of ice that is white and has an irregular surface. It forms when water droplets in supercooled FOG or drizzle freeze on contact with a surface that is at or below freezing temperature. Rime can also form by the deposition of water vapor. Once the process has commenced, water freezes or is deposited onto ice crystals that are already present. If there is a WIND, rime ice forms only on the sides of structures that face into the wind. Rime ice grows into elaborate, delicate, feathery shapes, but it can accumulate to a considerable thickness.

When the air is very dry its temperature may fall low enough for black frost or hard frost to form. This type of frost leaves plants blackened, but with no ice crystals on external surfaces. It occurs when the air is very dry, so the temperature can fall far below freezing without causing SATURATION. No frost forms on exposed surfaces, but moisture freezes inside plant tissues.

A drop in temperature that kills plants or prevents them from reproducing is known as a killing frost. As the falling temperature approaches freezing, small ice crystals start to form in the spaces between cells. This reduces the amount of water in the intercellular space, thereby increasing the concentration of compounds dissolved in the intercellular liquid. Water then flows from the cells by OSMOSIS to balance the concentration in the solutions on either side of the cell walls. If there is then a slow thaw, the ice will melt and the cells will reabsorb the water and recover, but if the temperature rises rapidly the water will be lost from the plant and cells will die from dehydration. Dehydration will also occur if the temperature remains below freezing for a prolonged period, because water will then be lost from the plant by SUBLIMATION. If flowers or fruits that have not yet set seed are damaged by frost, the resulting dehydration will prevent them from producing viable seeds. Seeds themselves are usually tolerant of frost because they contain little moisture.

The risk that growing plants will be damaged by frost is called the frost hazard. This can be expressed in several ways. It can be given as the probability forecast (*see* WEATHER FORECAST) that a killing frost will occur at a specified place on a particular date during the growing season. Alternatively, it can be expressed as the frequency with which killing frosts have occurred during the growing season in previous years. Or it can be a series of the dates on which the last spring and first autumn frosts have occurred over a number of years.

Many plants that grow naturally in high latitudes are able to tolerate freezing, and are said to be hardy. In plants that are not frost tolerant the loss of cell fluid leads to dehydration and may kill the affected cells. Hardy plants are believed to possess more flexible cell membranes and to allow their cells to shrink in size.

Depth hoar, also called sugar snow, is a layer of frost that forms by deposition just beneath the surface of a layer of snow. In Antarctica, depth hoar forms a layer up to 1 inch (2.5 cm) deep in autumn, beneath a layer of hard snow that is only about 0.2 inch (5 mm) thick. These alternate layers of depth hoar and snow are preserved and by cutting a trench down through the snow it is possible to use them to measure the amount of snow that fell each year.

Some places experience more frost than others. A frost hollow or frost pocket is a sheltered, low-lying area, usually small in extent, where temperatures fall below freezing more frequently than they do in the surrounding area. Frost hollows are found in hilly regions. At night, gentle KATABATIC WINDS carry cold air down the hillsides by gravity and into the hollows, where the air accumulates. The process is called ponding. By dawn there is often a sharp temperature difference, sometimes amounting to tens of degrees, between air in the hollow and the air near the tops of the surrounding hills. The effect is most severe in hollows that are shaded from the late afternoon Sun, because they begin to cool during the afternoon.

The part of a hillside that remains free from frost on nights when frost forms in the valley constitutes the frostless zone. As cold, dense air flows downhill by gravity it is replaced at a higher level by air that is warmer because of mixing with air above ground level. This keeps the hillside relatively warm and produces a valley INVERSION with a surface that is contoured in the same way as the ground surface.

The air flowing down the slope is not always colder than the air at the bottom, especially if TURBULENT FLOW has caused mixing with air from above the surface or there has been adiabatic warming (*see* ADIABAT). If the lower air is cooler, the warmer air rests above the cold air, reinforcing the inversion. The frostless zone then lies between the pool of cold air at the base of the hill and the exposed top of the hill.

Fujita Tornado Intensity Scale In 1945, the atomic bomb that was dropped on Hiroshima caused fierce firestorms (*see* FIRE) and these storms generated several TORNADOES. Tornadoes also developed in the firestorms that followed heavy bombing in several other cities—not only in Japan—and in 1923 there were tornadoes in Tokyo associated with the firestorms among the mainly wooden buildings that followed an earthquake. The Hiroshima tornadoes caught the attention of a young student, Tetsuya Fujita (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), who embarked on what became a lifelong study of them.

Fujita later moved to the United States and in 1968 he took the middle name Theodore. He became professor of meteorology at the University of Chicago and one of the leading world authorities on tornadoes.

He and his colleagues found there was a need to classify tornadoes. Ordinary winds were classified by the BEAUFORT WIND SCALE, in which the strongest wind was of hurricane force. The SAFFIR/SIMPSON HURRICANE SCALE expanded the Beaufort scale to include stronger hurricanes, but tornadoes were even stronger. In collaboration with Allen Pearson, formerly the chief tornado forecaster for the NATIONAL WEATHER SERVICE, in 1971 Fujita devised a six-point tornado scale, from F-0 to F-5. He also allowed the possibility of an F-6 tornado, but believed its effects would be indistinguishable from the total destruction caused by an F-5 tornado.

Even in a hurricane, it is usually possible to measure the wind speed, but in 1971 there was no instrument capable of withstanding the wind inside a major tornado and so the wind speed could not be measured. Also, the short lifetime of most tornadoes made measurement difficult. Instead, experiments revealed the type of damage winds of different speeds would cause and the speed of the wind in a tornado was then calculated from the type and extent of the damage it left behind.

The scale groups tornadoes as weak, strong, and violent, with two categories in each group. A weak tornado rated as F-0 may rip branches from trees and take loose tiles from roofs. An F-1 tornado will bring down trees and break windows.

Strong tornadoes cause more serious damage. At F-2, full-grown trees may be torn from the ground and mobile homes demolished. An F-3 tornado will flatten entire stands of trees, demolish some walls, and overturn cars.

Fujita Tornado Intensity Scale

	Wind Speed		
Rating	**MPH**	**km/h**	**Damage**
Weak			
F-0	40–72	64–116	Slight
F-1	73–112	117–180	Moderate
Strong			
F-2	113–157	182–253	Considerable
F-3	158–206	254–331	Severe
Violent			
F-4	207–260	333–418	Devastating
F-5	261–318	420–512 l	Incredible

The most extreme tornadoes are classed as violent. An F-4 tornado can reduce a building to a pile of rubble. One rated at F-5 will reduce buildings to rubble and then scatter the rubble over a wide area. It will severely damage steel-framed buildings and can pick up cars and carry them some distance before dropping them. These extreme events can also produce freakish effects. There have been accounts of houses lifted from the ground and then set down again—in one case a house was carried for 2 miles (3.2 km)—and a roof was blown 12 miles (19 km). In 1958, at El Dorado, Texas, a woman survived being blown through the window of her home and carried 60 feet (18 m).

In the United States, 69 percent of all tornadoes are weak, 29 percent are strong, and 2 percent are violent. On average, only one F-5 tornado strikes the U.S. each year. In April 1998, an F-5 tornado killed 33 people in Alabama, and on May 3, 1999, an F-5 tornado in Oklahoma demolished a fairly well-built house, smashing it into small pieces and scattering the debris downwind.

G

Gaia hypothesis The scientific proposal that on Earth, and by extension on any planet that supports life, the living organisms maintain conditions that are broadly favorable to themselves. In its weaker interpretation, the hypothesis proposes that the totality of living organisms, called the biota, actively participates in the cycling of nutrient elements and in the regulation of climate and the salinity of sea water. The strong interpretation holds that Earth itself is a single living organism, which maintains a constant environment suitable to itself.

James Lovelock (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) is the principal author of the hypothesis. In his first book on the subject (*Gaia: A New Look at Life on Earth,* published in 1979), Lovelock described Gaia as: "a complex entity involving the Earth's biosphere, atmosphere, oceans, and soil; the totality constituting a feedback or cybernetic system which seeks an optimal physical and chemical environment for life on this planet."

Development of the hypothesis began when Lovelock was working as a consultant to NASA at the Jet Propulsion Laboratory at Pasadena, California. The Viking program was being prepared. This program would place two landers on Mars, partly with the purpose of searching for life. Lovelock and his colleagues, including Dian Hitchcock, a philosopher employed to assess the logical consistency of the planned experiments, discussed how it might be possible to discover whether a planet supports life, probably based on organisms utterly different from those on Earth. They reasoned that any living organism would need to absorb some materials and excrete others. This would produce chemical changes in its environment that should be detectable as a disequilibrium in the composition of the atmosphere. Later, Lovelock explored the idea further in collaboration with Lynn Margulis. The name Gaia was suggested later by Lovelock's friend and neighbor the novelist William Golding. Gaia (or Ge) represents the Earth in Greek mythology.

The chemical disequilibrium of Earth's atmosphere becomes evident when its composition is compared with those of Mars and Venus, both of which consist predominantly of CARBON DIOXIDE and are in chemical equilibrium. Their state of equilibrium means that no chemical reactions among the component atmospheric gases are possible under the physical conditions that obtain. Earth's atmosphere is very different. It contains both METHANE (CH_4) and HYDROXYL (OH), for example, which react together to yield carbon dioxide (CO_2) and WATER (H_2O). Clearly, something must be constantly replenishing the CH_4, and the only reactions capable of this at the temperatures and pressures obtaining on Earth take place in bacterial cells.

Similarly, the atmosphere is predominantly (about 79 percent) NITROGEN, yet it also contains OXYGEN, and in the world as a whole there are about 100 LIGHTNING flashes every second, or more than 8 million every day. Lightning supplies the energy needed to break the bonds holding nitrogen and oxygen atoms together in their molecules in the air close to the flash. Nitrogen atoms (N) then react with oxygen atoms (O) to produce nitric oxide (NO) and then nitrate (NO_3). Nitrate is soluble and so it is washed to the surface by rain. After some millions of years all the nitrogen should have been removed from the air. Something—in fact, denitrifying bacteria—is constantly returning it.

At one time Earth's atmosphere contained very much more CO_2 than the approximately 3.5 percent it contains today. There is no mystery about where the gas went. It is present as carbonate (CO_3) in limestone and chalk rocks. These are among the most abundant of surface rocks, and they represent a huge store of what was once atmospheric carbon. There is a set of inorganic chemical reactions that convert CO_2 to CO_3, but these proceed too slowly to account for the quantity of carbonate rocks that have been deposited over the time the planet has existed. Biological reactions are much faster. These involve combining CO_2 with calcium (Ca) to produce calcium carbonate ($CaCO_3$). This is insoluble in shallow water, and many marine organisms use it to construct their shells. When the organisms die, the shells accumulate as sediment on the seafloor and are eventually heated and compressed to form rock. This is the mechanism by which atmospheric carbon is removed and "buried."

CO_2 is a greenhouse gas (*see* GREENHOUSE EFFECT), and removing it from the air has a climatic cooling effect. During the period since biological carbon burial began, the Sun has grown about 30 percent hotter, yet the surface temperature on Earth has never varied far from its present average of 59°F (15°C). According to the Gaia hypothesis, this is one way in which living organisms have maintained a constant climate.

Dimethyl sulfide, emitted by unicellular marine organisms, is the principal source of CLOUD CONDENSATION NUCLEI over the open ocean. Cloud formation helps to regulate the sea-surface temperature, and so this is another example of a biological influence on climate.

The Gaia hypothesis has become widely known, but it has always been scientifically controversial. It is difficult to see how it can be reconciled with evolutionary biology, for example. Nevertheless, it has influenced scientific thinking on a number of practical issues connected with the biological response to environmental change. One of these has led to bioremediation, which is the use of biological organisms to clean up environmental pollutants. The organisms are usually bacteria that may have been genetically modified for the purpose.

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Galveston A port and vacation resort in Texas that in 1900 suffered the worst hurricane disaster in American history. The TROPICAL CYCLONE formed in the Caribbean on August 27 and reached Galveston on September 8.

The town of Galveston lies on Galveston Island, a barrier island that is nowhere more than 3 miles (5 km) wide and is an average 4.5 feet (1.4 m) above sea level; the highest point on the island is 8.5 feet (2.6 m) above sea level. At the time of the storm it was linked to the mainland by one bridge suitable for pedestrians and horse-drawn vehicles and two rail bridges.

In 1900, Galveston was a prosperous port with a population of approximately 38,000. There were no satellites in those days to monitor the development of the STORM and track its approach. One Galveston resident, Isaac Cline, the local forecast official of the U.S. Weather Bureau, recognized from the sea conditions that a hurricane was approaching. Cline tried to warn people, but few heeded him. People went about their

Galveston, after the 1900 hurricane and storm surge. In terms of loss of life, this was the greatest natural disaster in the history of the United States. *(Historic NWS Collection)*

ordinary business, and some paused to watch the dramatic waves pounding the shore.

On the morning of September 8, the weather deteriorated rapidly and the sea level rose. By noon all the bridges linking Galveston to the mainland were flooded and impassable. Waves smashed buildings near the shore and the wind, of 77 MPH (124 km/h) gusting to 120 MPH (193 km/h), destroyed buildings farther inland. The city was flooded to a depth of 4 feet (1.2 m). The hurricane began to move away from Galveston at about 10 P.M. and the wind abated.

The following morning the damage became apparent. The city was largely reduced to rubble and smashed wood. No one knows how many persons lost their lives, but the figure is between 6,000 and 12,000. A further 5,000 had been injured. More than 2,600 homes had been destroyed, and about 10,000 people were homeless. The survivors were without water and power and, with the telephone and telegraph lines down, they had no way of communicating with the mainland. The storm finally dissipated on September 15.

In response to the catastrophe, the Galveston community built a solid concrete sea wall 4.5 miles (7.2 km) long and 17 feet (5.2 m) high) and then lifted 2,156 houses to raise the ground level in the lowest part of the town to the level of the top of the sea wall. The strong sea wall withstood an even stronger storm in September 1961.

gas laws The physical laws by which the TEMPERATURE, pressure, and volume of an ideal gas are related. These were discovered by Robert Boyle (1627–1691), Edmé Mariotte (c. 1620–1684), Jacques Charles (1746–1823), and Joseph Gay-Lussac (1778–1850). (*See* APPENDIX I: BIOGRAPHICAL ENTRIES.)

In 1662, Boyle found that gases can be compressed. When he applied pressure to gas, by pouring mercury into the long, open end of a J-shaped tube that was sealed at the other, shorter end, he observed that the volume of the gas decreased. Boyle found that the volume of the gas was inversely proportional to the amount of pressure to which it was subjected—the greater the pressure, the smaller the volume. From this he calculated that pV = a constant, where p is the pressure and V the volume. In English-speaking countries this is known as Boyle's law.

About 15 years later, Mariotte independently reached the same conclusion, but with an important addition. Mariotte noticed that when a gas is heated it expands, and when it is cooled it contracts. It follows, therefore, that pV = a constant is true only if the temperature remains constant. This improved version is known in French-speaking countries as Mariotte's law, and because his version is more complete there is a case for adopting the name Mariotte's law in English-speaking countries as well.

In about 1787, Jacques Charles repeated experiments performed by Guillaume Amontons (1663–1705; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). Amontons had discovered that the volume of a gas changes with its temperature, provided the pressure under which it is held remains constant (allowing it to expand). Charles discovered the amount by which its volume changes with a given change in temperature. This is known as Charles's law, and is written as $V \div T$ = a constant, where T is the temperature.

Charles's law can also be expressed as: $V_1/V_2 = T_1/T_2$, where V_1 and T_1 are the initial volume and temperature and V_2 and T_2 are the final volume and temperature. Charles did not publish his law, however, and it was discovered again, independently, by Joseph Gay-Lussac, who did. For this reason it is sometimes known as Gay-Lussac's law.

Charles found that for every degree the temperature rises the volume of a given quantity of gas increases by $1 \div 273$ of its volume at 0°C, and for every degree that the temperature falls, the volume of the gas decreases by the same amount. At a temperature of -273°C, therefore, the volume should reach zero and no lower temperature can exist. This temperature is known as absolute zero (*see* TEMPERATURE SCALES).

A third law, known as the pressure law, is derived from the first two laws. It states that the pressure within a gas is directly proportional to its temperature, provided that the volume remains constant.

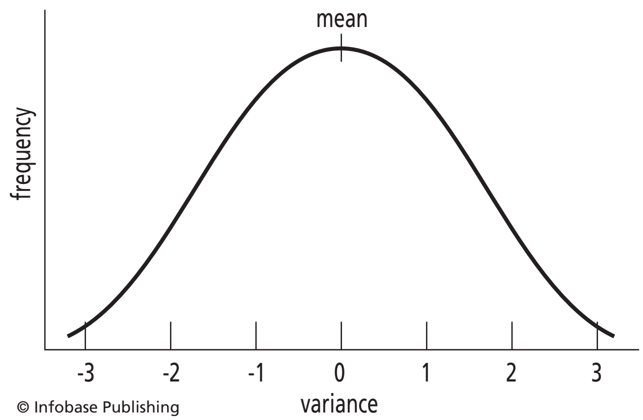
The three laws can be combined into a single equation of state also known as the ideal gas law: pV = a constant, from which a universal gas equation can be derived. This is $pV = nR_*T$, where n is the amount of gas in moles and R_* is the gas constant (8.31434 J/K/mol). In the case of air, which is unconfined and so has no precise volume, the equation substitutes the density for the volume. In meteorology, therefore, the equation is $p = \rho RT$ where ρ is the air density and R is the specific gas constant for air (= $10^3 R_* \div M$, where M is the relative molecular mass). Since air is a mixture of gases, each with its own specific mass and molecular weight, M has to be calculated from the individual molecular weights of its constituents. This shows that for dry air in which the component gases are well mixed $M = 29.0$ g and the specific gas constant is 287 J/K/kg.

An additional law was proposed in 1803 by the English chemist John Dalton (1766–1844; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). Dalton's law states that in a mixture of gases, the total pressure is the sum of the pressures that each component of the mixture would exert if it alone occupied the same volume at the same temperature. This can be written as: $p = \Sigma_i \rho_i R_i T$, where p is the total pressure, Σ_i is the sum of the pressures exerted by the constituent gases, ρ_i is the density of each gas, R_i is the *specific gas constant* for each gas, and T is the absolute temperature (the temperature in kelvins). The pressure exerted by each constituent gas is called the PARTIAL PRESSURE for that gas.

The gas constant is a value used when the gas laws are combined into the equation of state. The universal gas constant applies to 1 mole of an ideal gas and has a value of 8.314 J/K/mol. The specific gas constant (R) varies from one gas to another. It has a value of $R = 10^3 R*/M$, where $R*$ is the universal gas constant and M is the molecular weight of the gas (the value must be multiplied by 1,000 because moles are defined in grams and the unit of mass is the kilogram). Air is a mixture of gases. Constants for each of them can be added together, giving a specific gas constant for air with a relative molecular mass of 29.0 of $R = 287$ J/kg/K (17.3 calories per pound per degree Fahrenheit). This is true for dry air, but only approximately true for moist air, because the presence of water vapor reduces the density of moist air to about 0.5 percent less than that of dry air at the same temperature and pressure. The difference becomes important in precise calculations of conditions inside clouds. For these, the use of the VIRTUAL TEMPERATURE gives moist air the same gas constant as dry air.

Real gases obey the gas laws to only a limited extent. They come closest to obeying them at low pressures and high temperatures. The ideal gas to which the gas laws apply under all conditions is one composed of very small molecules and in which there are no forces acting between the molecules.

Gaussian distribution (**normal distribution**) In statistics, the way that values of a variable quantity appear on a graph when there is an equal area beneath the graph curve to either side of the MEAN. The curve is shaped like a bell, and its maximum height marks the mean. It is called normal because this is the distribution that occurs in the absence of any factor forcing it in one direction or the other.



When the values of a variable quantity are plotted against the frequency of their occurrence, a Gaussian distribution appears as a bell-shaped curve in which the value of the variables smaller than the mean is equal to that greater than the mean.

Pollutant particles inside a plume rise (*see* CHIMNEY PLUME) are distributed in this way, for example, so the mathematics of Gaussian distribution can be used to calculate their position.

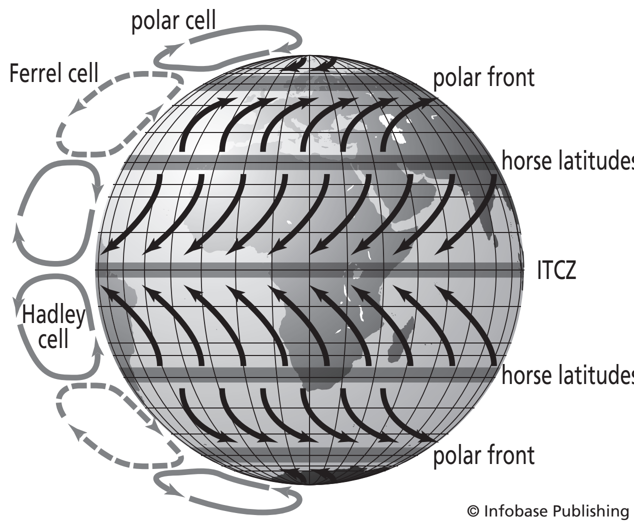
The German mathematician, physicist, and astronomer Karl Friedrich Gauss (1777–1855) is usually credited with having devised the equations describing this distribution, but it is possible that they were discovered earlier by the French mathematician Abraham de Moivre (1667–1754).

general circulation The general circulation comprises all of the movements of the atmosphere by which heat is transported away from the equator and into higher latitudes, winds are generated, and CLOUDS and PRECIPITATION are produced. It includes all of the air motion that results in what we experience as weather.

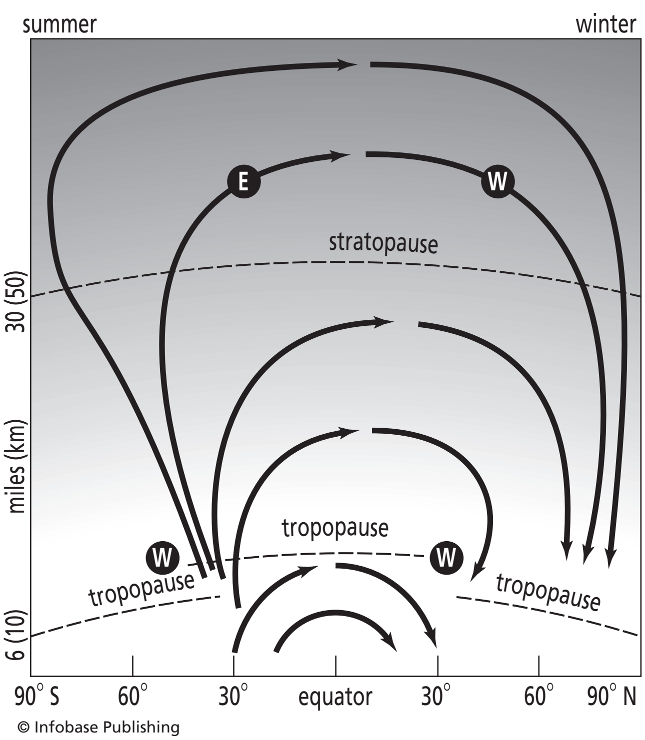
People have always been interested in the weather, and throughout history philosophers and scientists have sought explanations for meteorological phenomena. These phenomena occur on a local scale, but they realized that general explanations could be applied to them. Whatever it is that causes a THUNDERSTORM, gale, FOG, or BLIZZARD, can cause these events anywhere. Explain one thunderstorm and you have explained all thunderstorms. Other events are not explained so easily. The MONSOON, for example, is not the same as the many rainstorms it brings.

It was not until late in the 17th century that the idea of a global weather system began to develop, and interest in it was triggered by the growth of world trade. Sailing ships carrying cargoes around the world encountered belts where winds were steady and reliable. The most reliable of these were the trade winds (*see* WIND SYSTEMS), and the English astronomer Edmund Halley attempted to explain these by proposing a movement of air away from the equator at a high level and the return of air near the surface. George Hadley improved on this explanation half a century later, but it was not until the 19th century that the American meteorologist William Ferrel completed the description. (*See* APPENDIX I: BIOGRAPHICAL ENTRIES for more information about Halley, Hadley, and Ferrel.) The result is known as the three-cell model.

The difference between the Halley and Hadley explanations centered on the eastward component of the trade winds, which Halley failed to account for and,



The three-cell model describes the general circulation of the atmosphere by three vertical cells, the Hadley, Ferrel, and polar cells. The arrows indicate the direction of surface winds.



The general circulation in the stratosphere, showing the levels of the tropopause and stratopause. The letters *E* and *W* indicate the directions of the prevailing stratospheric winds in the middle latitudes of both hemispheres.

as Ferrel discovered much later, Hadley accounted for incorrectly. Their general description was correct, however. Warm air rises over equatorial regions and moves away from the equator. Cold air subsides over the poles. Cool air flows toward the equator.

In the early years of the 20th century, Vilhelm Bjerknes, Tor Bergeron, and their colleagues at the BERGEN GEOPHYSICAL INSTITUTE filled in many of the details of this very general outline. They introduced the concepts of the AIR MASS and the fronts that separate them (*see* FRONTOGENESIS; *see also* APPENDIX I: BIOGRAPHICAL ENTRIES for more information about Bjerknes and Bergeron).

The next major advance came with the launch of observation satellites that were able to view the Earth from above. These provided constant monitoring of cloud patterns, temperature, ocean waves, and changing vegetation over large areas and eventually over the entire planet. The introduction of powerful supercomputers made it possible to perform the millions of calculations needed to construct models of the general circulation. It is these models that are used in estimating the climatic effects of various events, including the enhanced GREENHOUSE EFFECT.

Until recently, little was known about the stratosphere (*see* ATMOSPHERIC STRUCTURE). Scientists now know that it has its own general circulation. This is quite distinct from the circulation in the troposphere.

Stratospheric air rises over the Tropics, driven by rising tropospheric air, and subsides over the poles. This vertical movement produces variations in the height of the tropopause, which is highest over the equator and lowest over the poles, with sharp "steps" in its height at the subtropical front and polar front (*see* front). These steps are usually represented as being merged into a single step in each hemisphere. Within the stratosphere, air radiates warmth into space. This has a cooling effect on the atmosphere. At the same time, however, the absorption of ultraviolet radiation by ozone raises the temperature. Consequently, the temperature rises with increasing height, reaching a maximum over the pole in the summer hemisphere and a minimum over the pole in the winter hemisphere.

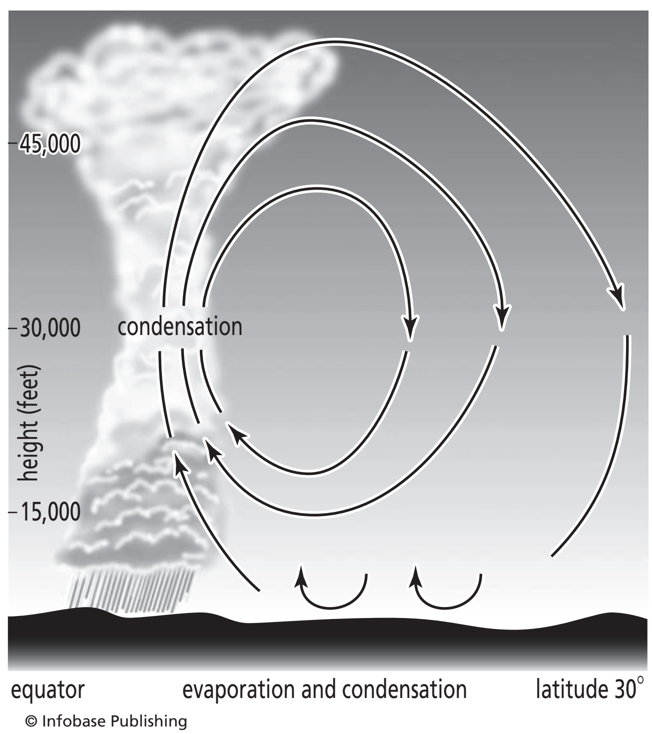
The three-cell model is a description of the general circulation of the atmosphere that is widely used by meteorologists and climatologists. It is known to be an oversimplification, but it nevertheless provides a good approximation of the way the atmosphere behaves. The general circulation transports warm air from the equator to the poles and returns cool air to the equator. This is achieved by a system of vertical cells. These are of three types, and hence the name of the model.

The cell responsible for the equatorial circulation is a modified version of the cell described in 1753 by George Hadley, and it is known as the Hadley cell. Hadley suggested that air in contact with the surface is heated more strongly at the equator than it is anywhere else. The warm air rises and flows away from the equator at a very high level. By the time it reaches the poles it is very cold and subsides. It then returns to the equator at a low level, completing the circulation within the convection cell. As the air moves across the surface, it is deflected by the rotation of the Earth beneath it. It is this deflection that swings the airflow into a more westerly direction, so it arrives at the equator as northeasterly and southeasterly winds. Hadley imagined there was a single convection cell in each hemisphere.

It is not quite so simple as Hadley supposed. In the first place, the Coriolis effect, which had not yet been discovered but was the cause of the deflection on which Hadley's account relied, is very weak in the Tropics and its magnitude is zero at the equator. In 1856, William Ferrel pointed out that the real reason for the deflection is the conservation of angular momentum in the moving air.

Nor does the cell extend all the way from the equator to the poles. Air rises at the equator and subsides in the subtropics, at about latitude 30° in both hemispheres. Subsiding air produces the subtropical highs. If there were a single convection cell, there would be a continuous subtropical region of high pressure associated with the subsiding side of the cell. In fact, there are several subtropical highs separated by lows. This demonstrates that there is not one convection cell, but as many as there are subtropical highs. There are about five in winter and four in summer. However, the intensity of the convection cells and the subtropical highs appear to be unconnected.

It is only in spring and autumn that there are two sets of cells arranged symmetrically on either side of the equator. This is because the equatorial trough (*see* Intertropical Convergence Zone), which is the center of the convergence and rising air, moves north and south with the seasons. The most important cells lie on the winter side of the equator (in the Southern Hemisphere during the Northern Hemisphere winter) and air spilling out from them crosses the equator into the summer hemisphere. In addition, horizontal air movements are now known to contribute significantly



In Hadley cells, air rises over the equator, cooling as it does so and producing clouds and high rainfall. The air moves away from the equator at a high level and subsides in the Tropics and subtropics.

to the transport of heat away from the equator. These movements are especially important in middle latitudes, where weather systems transport heat.

In the modern understanding of the Hadley cells, air rises by convection at the equatorial trough. The air is moist and as it cools adiabatically (*see* ADIABAT) its water vapor condenses. Condensation releases LATENT HEAT, increasing the instability of the air (*see* STABILITY OF AIR) and producing giant cumulonimbus clouds (*see* CLOUD TYPES). This accounts for the heavy rainfall of the humid Tropics.

Air moves away from the equator at the level of the tropopause. This air is extremely dry, because its moisture condenses as the air rises through the troposphere. As it moves away from the equator the air loses heat by radiation. This increases its DENSITY. At the same time, the magnitude of the Coriolis effect increases, deflecting the air to the east. By the time it reaches the subtropics, much of the air is moving in an easterly direction. The high-level flow of air toward the poles is concentrated mainly on the western sides of the subtropical highs. Air accumulates and this also increases its density. Consequently, the air subsides at about latitude 30° in both hemispheres. As it descends, the dry air warms adiabatically (*see* ADIABAT), and as its temperature rises, its relative HUMIDITY decreases. The air becomes still drier.

By the time it reaches the surface the air is hot and dry. The subsiding air produces a belt of high surface pressure in the subtropics. This reinforces the aridity of the climate by producing an outward flow of air at the surface, which prevents moister air from moving into the region.

Over the poles, where the land and sea surfaces are extremely cold, the air is chilled at the surface and contracts. Air is drawn downward, producing high surface pressure and an outflow of air away from the poles. This makes up one side of the polar cells.

Both the polar and Hadley cells are thermally direct cells, which is to say they are driven directly by the surface temperature. The polar and Hadley cells are separated by midlatitude cells that were first discovered by William Ferrel and are known as Ferrel cells. The Ferrel cells are indirect cells, in that they are not driven by convection, but by the direct Hadley and polar cells to either side of them. Air movement is weak in the Ferrel cells, with the result that the predominant air movement in middle latitudes is controlled by the

In the polar cells, air subsides over high latitudes and diverges at the surface, flowing away from the poles and producing the polar easterlies. Where the air encounters the polar front it rises and flows back toward the poles.

weather systems that are carried by the generally westerly airflow.

When subsiding air reaches the surface on the poleward side of the Hadley cells it divides. Some returns to the equator and some moves toward higher latitudes. The subsiding air of the Hadley cells and the poleward movement of air near the surface form one side and the base of the Ferrel cells. Near the polar front, the air moving toward the pole meets air moving away from the pole in the polar cells. Convergence makes the air rise and produces low pressure at the surface. At the height of the tropopause the air divides. Some flows toward the poles, to complete the polar cells, and some flows toward the equator to complete the Ferrel cells.

As air moves toward or away from the equator, it is deflected by the Coriolis effect. Near the surface this produces only a slight deflection in low latitudes, where the magnitude of the Coriolis effect is small (it is zero at the equator), but winds are affected by VORTICITY. This produces the low-level northeasterly and southeasterly trade winds. The belt where the trade winds from both hemispheres meet is called the Intertropical Convergence Zone (ITCZ).

High-level winds in the Hadley cell are westerly above about 25,000 feet (7,600 m) over the equator and above about 5,000 feet (1,500 m) over the subtropics. Winds in midlatitudes are from the west at all altitudes. These are the prevailing westerlies (*see* WIND SYSTEMS). They include the westerly JET STREAM.

At the surface, there is a belt where the prevailing westerlies flow away from the equator, as southwesterlies in the Northern Hemisphere and northwesterlies in the Southern Hemisphere, and the trade winds flow toward the equator. This produces the horse latitudes (*see* WEATHER TERMS), where winds are light and variable.

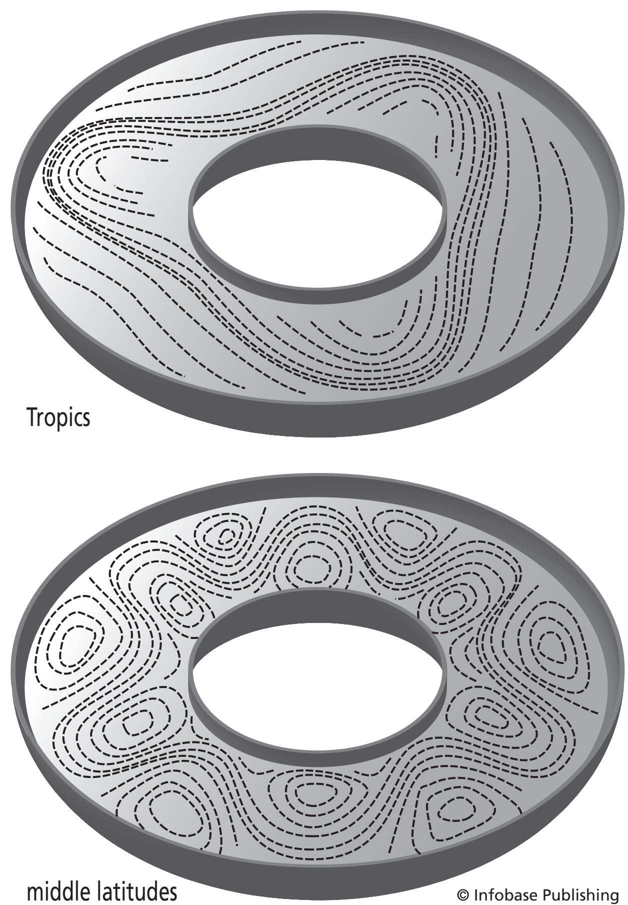
Surface winds in the polar cells, flowing toward the equator, are easterlies. At high level, winds flowing away from the equator are westerlies.

Although the three-cell model provides a useful general outline, it should not be taken too literally. There is not one Hadley cell in each hemisphere, for example, but several. The winds predicted by the model should be GEOSTROPHIC. This would produce easterly winds at high level in midlatitudes, but the prevailing midlatitude winds are westerlies at all levels, although they are dominated by ROSSBY WAVES and the variations in them through the index cycle (*see* ZONAL INDEX). The simple description of the indirect Ferrel cell is also inaccurate. In midlatitudes, heat is transferred mainly by large-scale horizontal waves and by smaller disturbances embedded within them.

Dishpan experiments are laboratory experiments that simulate the general circulation of the atmosphere and demonstrate the importance of the horizontal transport of heat and momentum. By the 1920s, some scientists were beginning to suspect that the three-cell model does not tell the whole of the story. They thought it possible that, in addition to the vertical transport of the three cells, heat and momentum also traveled horizontally. At the time there seemed no way to test the idea. The prevailing winds that blow horizontally near the surface were well known, but to test the idea the scientists needed to know how the air was moving in the upper troposphere, an inaccessible region about which little was known.

The three-cell model was based on what happens when a pan of water, or "dishpan," is heated over a stove. Warming at the base and cooling at the top establish one or more convection cells. The atmosphere is not really like a dishpan on a stove, however, because it is subject to forces that arise from the rotation of the Earth and also because the equator is not a simple point source of heat.

That is how the laboratory dishpan was invented. It is shallow and shaped like a doughnut. The center is kept cold, while heat is applied around the outer edge,



The dishpan is an open-topped, doughnut-shaped container that is cooled at the center and warmed at the outer edge. When it is filled with water and made to rotate, currents develop in the water with a pattern that is identical to the pattern made by the horizontal movement of the atmosphere.

and the dishpan rotates. It is filled with water to which drops of dye are added. As currents develop in the water, the dye they carry traces their directions.

Water in a rotating dishpan represents the atmosphere as seen from above the North or South Pole (depending on the direction of rotation). The outer rim represents the equator and the cold center is the pole.

A simple refinement of the device makes it possible to simulate the atmosphere within particular zonal (latitudinal) belts. All this requires is an adjustment of the rate of rotation. Slow rotation produces a "low-latitude atmosphere," and faster rotation produces a simulation of atmospheric motion in higher latitudes.

Dishpan experiments showed that in addition to movement through the vertical convection cells, air also develops horizontal waves with a very long wavelength (*see* WAVE CHARACTERISTICS). These are now called Rossby waves. In the Tropics there are about three waves at any time, with a wavelength of about 8,300 miles (13,340 km). In middle latitudes there are about six waves and the wavelength is about 5,860 miles (9,435 km). The middle latitude circulation also generates many eddies. All the waves move slowly eastward, and those in middle latitudes periodically change in amplitude over an index cycle.

These large waves carry warm air away from the equator and cold air toward the equator, and they also confirm that the atmospheric circulation in middle latitudes differs substantially from that of the Tropics. They also show that the surface wind belts—the low-latitude easterlies, middle-latitude westerlies, and high-latitude easterlies—are produced by traveling waves, not by the meridional (north–south) circulation. Results from dishpan experiments confirm predictions of atmospheric behavior that have been made mathematically and by computer simulations.

The part of the general circulation of the atmosphere that consists of large-scale, persistent features is called the primary circulation. Although details of these features change from time to time, their overall character remains constant over large areas of the world. The primary circulation is driven by the latitudinal differences in the amount of solar radiation that is received at the surface. These differences produce the Intertropical Convergence Zone and equatorial trough, as well as the subtropical highs. The secondary circulation is the part of the general circulation consisting of relatively small-scale, short-lived features that are superimposed on the more permanent features of the primary circulation. Frontal systems, CYCLONES, and ANTICYCLONES dominate the secondary circulation in middle latitudes. The tertiary circulation is the circulation of air that takes place on a very local scale, such as a THUNDERSTORM, local wind, FÖHN WIND, or TORNADO.

geomorphology Geomorphology is the scientific study of landforms and how they develop. It is concerned with the effects of EROSION and WEATHERING on the rocks that lie at the Earth's surface.

Climatic geomorphology is a branch of geomorphology that began toward the end of the 19th century and that concentrates on the effects of climate in shaping the surface of the planet. Climatic geomorphologists have defined 10 types of climatic processes that form landscapes and have produced a map of the world showing where each of them occurs.

geopotential height A value for height above mean sea level that takes account of the increase in gravitational acceleration with latitude. The latitudinal change in gravitational acceleration is due to the Earth's shape and rotation. The Earth is oblate—the surface is closer to the center of the Earth at the poles than it is at the equator and the balance between the gravitational force and the inertial force changes due to the Earth's rotation (*see* CENTRIPETAL ACCELERATION).

The gravitational force always acts directly toward the center of the Earth with a magnitude that varies according to the INVERSE SQUARE LAW. The inertial force acts away from the axis of the Earth's rotation with a magnitude that is directly proportional to the distance from that axis. Consequently, the inertial force is greatest at the equator and zero at the poles. A component of the inertial force acts against the gravitational force, but its effect decreases with distance from the equator. Therefore, the effect of the gravitational force increases with distance from the equator.

The gravitational potential, or geopotential, energy of a body is equal to the work that must be done to raise that body from mean sea level to a given height. Since this amount of work varies with the changes in the gravitational force, the geopotential energy can be used to designate height. The geopotential height is the height above mean sea level at which a body would have to be located in order to have the same geopotential if the gravitational acceleration were the same everywhere.

Geopotential heights are widely used by meteorologists, because particles that are free to move usually flow downhill, from regions of higher to lower potential energy. This means that if a PARCEL OF AIR is imagined as being located on a surface at a constant geometric height (measured as vertical distance) it will experience a component of the gravitational force moving it toward the equator, where the geopotential is lower. If the location of the parcel is given as a surface at a constant geopotential height, the forces acting on it will be equal in all directions and so it will remain stationary.

Geopotential height is measured in geopotential meters, which are units of energy per unit mass. One geopotential meter is equal to 1/9.8 m^2/s^2. If the values for gravitational acceleration are known, ordinary (geometric) heights can be converted to geopotential heights without altering any of the equations that are used in calculating atmospheric behavior. This greatly simplifies the calculations.

Geostationary Operational Environmental Satellite (GOES) A series of U.S. weather satellites that transmit data to the National Oceanic and Atmospheric Administration (NOAA) receiving station at Wallops, Virginia. Two GOES satellites are operational at any time, both in a geostationary ORBIT. GOES-8 orbits at 75°W and observes eastern North America, the western Atlantic, and western South America. GOES-10, which replaced GOES-9 at the end of its useful life in July 1998, orbits at 135°W and observes western North America, the eastern North Pacific as far as Hawaii, and the eastern South Pacific. The satellites transmit their data every half-hour.

Further Reading

NOAA. "GOES Project Science." NOAA. Available online. URL: http://rsd.gsfc.nasa.gov/goes/. Accessed December 14, 2005.

———. "Geostationary Operational Environmental Satellites." NOAA. Available online. URL: http://www.oso.noaa.gov/goes/. Accessed December 14, 2005.

geostrophic wind Suppose there is an area of low atmospheric pressure in air that is stationary. A PRESSURE GRADIENT will exist across the isobars (*see* ISO-) surrounding the low-pressure center and therefore there will be a PRESSURE GRADIENT FORCE causing air to move toward the center. As soon as it starts to move, the air becomes subject to the CORIOLIS EFFECT. This deflects it to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, acting at right angles to the direction of flow.

A component of the Coriolis effect acts in the same direction as the wind. This increases the wind speed, but the magnitude of the Coriolis effect varies in proportion to the wind speed, so as the wind accelerates the deflection also increases. The process continues until the pressure gradient force and Coriolis effect balance each other and the wind blows parallel to the isobars. Should the pressure gradient force increase, causing the wind to accelerate and turn toward the low-pressure center, the Coriolis effect will also increase, correcting the wind. This is then called the geostrophic wind, from the Greek *ge* meaning "Earth" and *strepho* meaning "to turn," because the direction of the wind is turned by the Earth.

The geostrophic wind is a wind that blows parallel to the isobars. Close to the surface, however, FRICTION slows the wind, reducing the magnitude of the Coriolis effect and causing the wind to blow across the isobars at an angle of 10° to 30° depending on the speed of the wind and the local topography. Friction has no effect above the PLANETARY BOUNDARY LAYER, which is where the winds are geostrophic. The lowest height at which the wind flow becomes geostrophic is known as the geostrophic wind level or gradient wind level. This is above the planetary boundary layer, at an altitude of 1,650–3,300 feet (500–1,000 m).

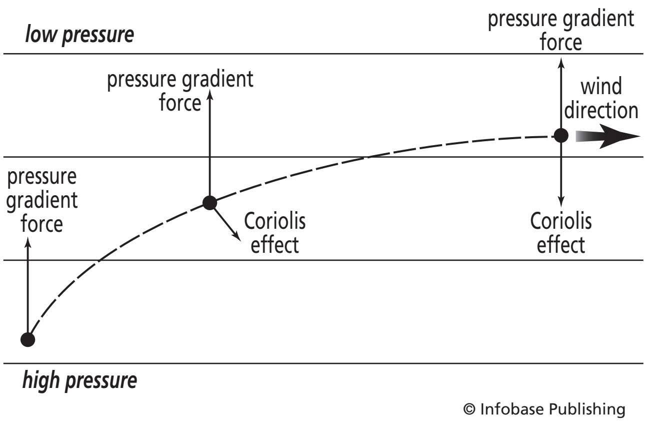
The geostrophic equation is used to calculate the speed of the geostrophic wind. The equation is:

$$V_g = (1/(2\Omega \sin \phi\rho)(\delta p/\delta n)$$

where V_g is the geostrophic wind velocity, Ω is the angular velocity of the Earth (= 15°/hr = $2\pi/24$ rad/hr = 7.29×10^{-5} rad/s), ϕ is the latitude, ρ is the air density, and $\delta p/\delta n$ is the horizontal pressure gradient. $2\Omega \sin\phi$ is known as the Coriolis parameter and sometimes designated by f, so the equation then becomes:

$$V_g = (1/f\rho)(\delta p/\delta n)$$

A diagram drawn from solutions of the geostrophic equation, from which the geostrophic wind speed can be read is called a geostrophic wind scale.



The geostrophic wind is driven by the pressure gradient force (PGF) at right angles to the isobars (the horizontal lines) from the region of high pressure and toward the region of low pressure. The Coriolis effect (CorF) swings the wind to the right (in the Northern Hemisphere) and accelerates it, because a component of the CorF acts in the same direction as the wind. Acceleration increases the CorF until eventually the PGF and CorF are in balance, with the wind blowing parallel to the isobars.

The angle between the direction of a steady wind and the isobars is known as the angle of indraft. This angle indicates the extent to which the wind departs from the geostrophic wind. The angle of indraft is said to be positive when the wind direction is toward the area of low pressure (which is almost invariably the case). The angle is greater over land than over the sea, because friction is greater over land. Over the sea the angle is sometimes zero and occasionally negative when a strong THERMAL WIND blows toward a high-pressure region across a shallow pressure gradient.

When the pressure gradient force and Coriolis effect above the planetary boundary layer are precisely equal, the wind is said to be in geostrophic balance. A difference between the wind speed that is observed and that of the geostrophic wind is called a geostrophic departure. Winds in the vicinity of the entrance region of the polar front JET STREAM tend to be supergeostrophic, because they are being accelerated in the direction of the wind. The GRADIENT WIND around an ANTICYCLONE is also supergeostrophic, although the effect is small. A subgeostrophic wind blows with less force than the geostrophic wind. The gradient wind around a CYCLONE is subgeostrophic. Accelerations that are at right angles to the wind direction also occur and cause geostrophic departures.

A wind that blows above the planetary boundary layer at a speed which differs from that of the geostrophic wind predicted by the pressure gradient is called an ageostrophic wind.

The transport of some substance or atmospheric property by the geostrophic wind is called a geostrophic flux.

A value that is calculated for the strength of the easterly winds in the subtropics between latitudes 20°N and 35°N, known as the subtropical easterlies index, is based on the difference in the average sea-level atmospheric pressure between these latitudes. It is expressed in meters per second as the east–west component of the geostrophic wind.

geothermal flux The flow of energy from the interior of the Earth to the surface that is due partly to the impacts of the bodies that collided to form the planet and its subsequent gravitational collapse, but mainly to the decay of radioactive elements in and beneath the crust. The geothermal flux heats the atmosphere where the energy reaches the surface at geysers, thermal springs, and volcanoes.

Geothermal flux is the second largest source of energy affecting the atmosphere, but averaged over the entire Earth it amounts to no more than about 0.05 W/m^2. This is very small compared with proportion of the SOLAR CONSTANT that reaches the surface.

glacial anticyclone (**glacial high**) The semipermanent regions of high AIR PRESSURE that cover the GREENLAND ICE SHEET and Antarctica.

glacial period (**ice age**) A prolonged time during which a substantial part of the surface of the Earth is covered by ice. In this sense, the term is somewhat vague, since "substantial" is not defined. Ice sheets cover a large area at the present time, so by this definition the Earth might be experiencing a glacial period now, but climatologists consider the present climatic conditions to be typical of an INTERGLACIAL period, named the Flandrian.

The glacial theory, that at one time most of northern Europe, northern Asia, and North America had been covered by ICE SHEETS, was first advanced during the 1830s and 1840s by a number of scientists, of whom Louis Agassiz (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) was the best known. The historical period during which this occurred later came to be called the PLEISTOCENE epoch. The theory was used to explain various geomorphological features and the extinction of certain animals, such as mammoths. Scientists have since expanded the theory to include a number of glacial periods rather than the single one that was originally supposed to have taken place.

A period when GLACIERS and ICE SHEETS reached their maximum extent is called an icehouse period. It is possible that there have been times when the entire surface of the Earth was covered by ice (*see* SNOWBALL EARTH). Less extreme icehouse periods have occurred many times in the history of the Earth and evidence for some of them is found in seabed sediments. They appear to develop at intervals that are related to the MILANKOVITCH CYCLES. A time when there were no glaciers or ice sheets anywhere on Earth is called a greenhouse period. Such periods have occurred many times in the history of the Earth, and evidence for some of them is found in seabed sediments. They also appear to develop at intervals that are related to the Milankovitch cycles.

The process of burying of an area beneath an ice sheet, as occurs during a glacial period is termed glaciation. The same term is used to describe the change of water droplets to ICE CRYSTALS in the upper part of a convective cloud (*see* CLOUD TYPES).

The term *glacial period,* usually abbreviated to glacial, is applied more precisely to a particular climatic episode that occurred in the past. The most recent of these to affect North America was the Wisconsinian glacial, which was equivalent to the Devensian glacial in Britain, the Weichselian glacial elsewhere in northern Europe, and the Würm glacial in the Alps. There have been several other glacial periods during the last 2 million years. They have been detected in several parts of the world and although dates often overlap, glacial periods in one region may not coincide precisely with those elsewhere. Consequently, there are separate names for the glacial periods of North America, northern Europe, and the European Alps. They are described here in alphabetical rather than date order. Glacials and interglacials are listed in date order in APPENDIX VII: PLIOCENE, PLEISTOCENE, AND HOLOCENE GLACIALS AND INTERGLACIALS.

The Anglian glacial period in Britain that lasted from approximately 350,000 years ago until about 250,000 years ago. It is equivalent to the Elsterian glacial of northern Europe and the Mindel glacial of the European Alps and partly coincides with the Kansan glacial of North America. Glaciers advanced and retreated several times during the Anglian. It was preceded by the Cromerian interglacial and followed by the Hoxnian interglacial.

The Devensian was the most recent glacial period in Britain. It began about 70,000 years ago, or possibly a little earlier, and ended about 10,000 years ago. The LAST GLACIAL MAXIMUM occurred about 21,000 years ago. It is known as the Weichselian glacial in northern Europe and Würm glacial in the Alps, and it is approximately equivalent in date to the Wisconsinian glacial of North America. The Devensian was preceded by the Ipswichian interglacial and followed by the present Flandrian interglacial.

The Donau glacial period occurred in Europe very early in the Pleistocene epoch and probably ended about 1 million years ago. Few traces of it remain. It was preceded by the Tiglian interglacial and followed by the Waalian interglacial. Donau is the German name for the River Danube.

The Günz was the earliest of the Pleistocene glacial periods of the European Alps to be dated. It lasted from approximately 800,000 years ago until about 600,000 years ago. It is equivalent to the Menapian glacial of northern Europe and the Nebraskan glacial of North America. It is named after an alpine river. The Günz was followed by the Günz–Mindel interglacial.

The Illinoian was a glacial period in North America that began about 170,000 years ago and ended about 120,000 years ago. Average temperatures during the Illinoian were 3.6–5.4°F (2–3°C) cooler than those of today. The Illinoian is approximately equivalent to the Mindel and Riss glacials of the Alps. It was preceded by the Yarmouthian interglacial and followed by the Sangamonian interglacial. The name is sometimes spelled Illinoisan.

The Kansan glacial period in North America began about 480,000 years ago and ended about 230,000 years ago. It is approximately equivalent to the Günz glacial of the European Alps. The Kansan was preceded by the Aftonian interglacial and followed by the Yarmouthian interglacial.

The Mindel was a glacial period of the European Alps that is the equivalent of the Anglian glacial of Britain and the Elsterian glacial of northern Europe. It partly coincides with the Kansan glacial of North America. It is named after an alpine river. The Mindel began about 350,000 years ago and ended about

250,000 years ago. It was followed by the Mindel–Riss interglacial; the interglacial preceding it has no name.

The Nebraskan glacial period in North America began about 800,000 years ago and ended about 600,000 years ago. It was preceded by predominantly warm conditions throughout pre-Nebraskan time from the start of the Pleistocene epoch 12.6 million years ago. The Nebraskan was followed by the Aftonian interglacial.

The Riss was a glacial period in the European Alps, named after an alpine river, that is equivalent to the Wolstonian glacial of Britain and the Saalian glacial of northern Europe and partly coincides with the Illinoian glacial of North America. The Riss began about 200,000 years ago and ended about 130,000 years ago. It followed the Mindel–Riss interglacial. The interglacial that followed it is known as the Riss/Würm interglacial in the European Alps and as the Eemian interglacial of northern Europe.

The Wisconsinian was the most recent glacial period in North America, following the Sangamonian interglacial. It began about 75,000 years ago and ended about 10,000 years ago. The last glacial maximum occurred about 20,000 years ago. The Wisconsinian is named for rock deposits found in Wisconsin. Ice sheets advanced and retreated several times during the Wisconsinian, but average temperatures throughout the glacial were about 11°F (6°C) lower than those of today. The Wisconsinian was preceded by the Sangamonian interglacial and followed by the present Flandrian interglacial. The Wisconsinian is approximately equivalent in date to the glacial known as the Devensian in Britain, Weichselian in northern Europe, and Würm in the Alps.

The Wolstonian glacial period in Britain began about 200,000 years ago and ended about 130,000 years ago. It is equivalent to the Riss glacial of the European Alps and the Saalian glacial of northern Europe and partly coincides with the Illinoian glacial of North America. It was preceded by the Hoxnian interglacial and followed by the Ipswichian interglacial.

glacier A large mass of ice that rests on the land surface. If it is attached to the solid surface but projects over the sea it is known as an ICE SHELF. Glaciology is the scientific study of ice in the air, lakes, rivers, oceans, and below ground, but especially the study of glaciers. Paleoglaciology is the study of glaciers and ICE SHEETS that existed in prehistoric times, based on the evidence they have left in surface rocks. The melting of an ice sheet or glacier that exposes the land beneath is called deglaciation.

Most glaciers flow, but very slowly (the expression "glacial speed" is applied to things that happen extremely slowly). A glacier in which the ice is flowing is said to be active. Large glaciers, such as those in Antarctica, move between about 0.4 and 4 inches (0.01–0.1 m) a day and valley glaciers at between 4 inches and 6.5 feet (0.1–2 m) a day, although they can occasionally move very much faster, at 165–330 feet (50–100 m) in a day.

Glaciers can be classified in several ways. The most widely used classification is based on the mechanism by which the ice flows, which is related to the temperature at the base of the glacier. In this system glaciers fall into three categories: cold glaciers, composite glaciers, and temperate glaciers.

A cold glacier, also called a polar glacier, is one in which the temperature of the ice at the base is well below the pressure melting point (*see* ICE) at all times of year. Cold glaciers occur in parts of Antarctica. They flow as a consequence of internal deformation of the ice, which is "squeezed" outward by the weight of overlying ice.

Composite or subpolar glaciers have edges that are at a temperature well below the pressure melting point throughout the year, but in the central part the ice temperature is above the pressure melting point except during winter. Thus they are cold (polar) glaciers at the edges and temperate or warm glaciers at the center. A composite glacier moves by pressure melting at the center and by internal deformation ("squeezing") at the edges. Glaciers in Spitzbergen are composite.

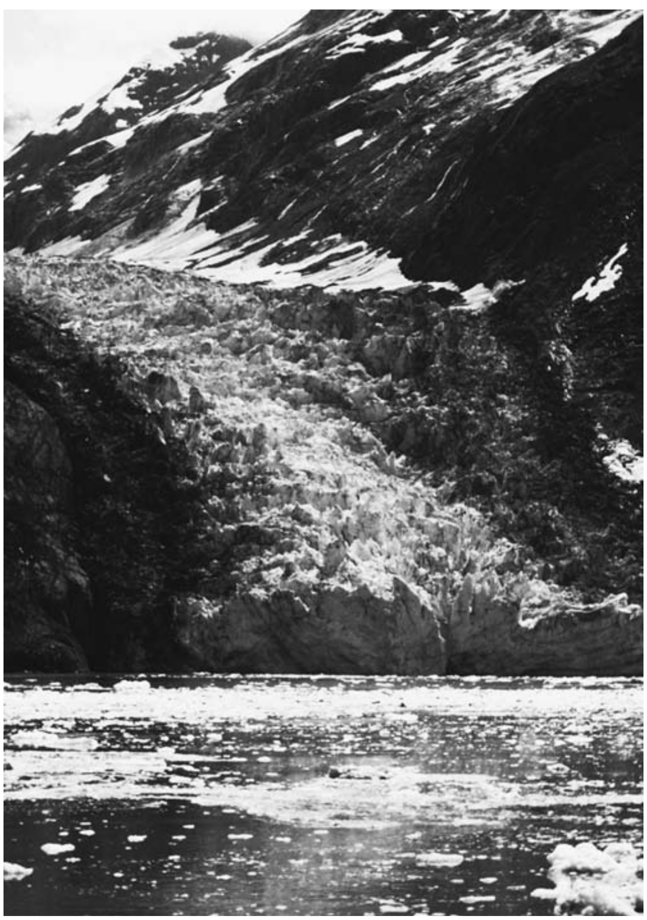
In a temperate or warm glacier, the temperature of the ice is above the pressure melting point except during winter. The glacier flows because pressure melting produces a thin layer of liquid water at the base of the ice, allowing the overlying ice to slide.

The most familiar image of a glacier is of one that is long, narrow, and confined between rocks on either side. This is properly known as a valley glacier, and there are two types. Alpine glaciers are fed by cirque glaciers. A cirque glacier is a mass of ice that lies in a hollow high in the mountains. Snow accumulates in the hollow forming a snowfield (*see* SNOW), compressing the ice at the base, which spills over the edge. Alpine glaciers are common in the European Alps and in the coastal mountains of Alaska.

Outlet glaciers are fed by an ice sheet or ice cap. The Vatnajökull ice cap in Iceland feeds several outlet glaciers and the GREENLAND ICE SHEET feeds several. The biggest outlet glacier in Greenland is the Humboldt Glacier. It is 62 miles (100 km) wide and flows north to enter the sea as a wall of ice more than 300 feet (118 m) high. It was an iceberg (*see* SEA ICE) that calved from the Illulissat (formerly Jakobshavn) Glacier, which sank the *Titanic* on the night of April 14–15, 1912.

Materials transported by glaciers and icebergs accumulate on the seabed as glaciomarine sediment. These materials can be identified and dated. They provide evidence of glacial advances and of HEINRICH EVENTS, which in turn provide evidence of past climates.

A line that marks the farthest point reached by a glacier at some time in the past is known as a glacial limit. Geomorphologists identify glacial limits by the presence of terminal or lateral moraines, outwash plains, which are accumulations of rock deposited by water flowing from a glacier, the channels of rivers that once carried meltwater from the glacier, and lakes lying in depressions hollowed out by the ice.



Johns Hopkins Glacier calving in Glacier Bay, Alaska, in August 1991 ***(Commander John Bortniak, NOAA Corps)***

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glacioisostasy The rise in the level of the land that takes place, very slowly, after an ICE SHEET has melted. During a GLACIAL PERIOD the weight of ice that accumulates on the surface depresses the crust. For example, in the course of the most recent glacial period the ice depressed the rocks beneath in Scandinavia by about 3,300 feet (1,000 m). Since the ice melted the land has risen by about 1,700 feet (520 m) and eventually it will rise by a further 1,600 feet (480 m). Eastern Canada is also rising for the same reason and is expected to rise by a further 650 feet (200 m).

Global Area Coverage Oceans Pathfinder Project (GAC) A study of sea-surface temperatures using data from measurements made by Advanced Very High Resolution Radiometers (*see* SATELLITE INSTRUMENTS) carried on the NOAA 7, NOAA 9, and subsequent odd-numbered NOAA satellites. The project is a collaboration between the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA), National Aeronautics and Space Administration (NASA), the University of Miami, and the University of Rhode Island. Its final results are checked at the Jet Propulsion Laboratory, a NASA facility located at the California Institute of Technology.

GAC forms part of the POLAR PATHFINDER PROGRAM initiated by the EARTH OBSERVING SYSTEM PROGRAM offices of NASA.

Global Atmospheric Research Program (GARP) A project that ran from 1968 until the early 1980s. Planning for it began in 1961, after President John F. Kennedy had proposed to the United Nations that orbiting space satellites should be used for peaceful purposes. Its aim was to observe the atmosphere from space over a long period in order to estimate its variability and the processes occurring within it, with a view to improving the quality of weather forecasts. GARP was organized by the WORLD METEOROLOGICAL ORGANIZATION and the International Council for Scientific Unions, and its first leader was the American meteorologist Jule Gregory Charney (1917–81).

The first GARP experiment, sometimes called the Global Weather Experiment (GWE) began on December 1, 1978, and ended on November 30, 1979. It involved scientists from more than 140 countries and was the biggest atmospheric experiment ever conducted up to that time. WORLD WEATHER WATCH ships and upper-air observations, weather buoys mainly in the oceans of the Southern Hemisphere, and commercial aircraft participated, as well as satellites. The data that were collected during the GARP years formed the basis of subsequent understanding of the dynamics of the atmosphere, and GARP also served as a model of how to arrange and manage a large-scale, international, scientific collaboration.

THORPEX, the successor to GARP, was launched in May 2003.

Global Drifter Program (**GDP**) A program that was planned in 1982 in response to the scientific need for data on surface temperatures and circulation patterns over large parts of the oceans. At that time data was available only from those regions that lie on shipping routes. The lack of data was especially serious for the Southern Hemisphere, where most of the sea areas are seldom visited.

The GDP uses low-cost, rugged buoys that drift in the ocean. The drifters measure water temperature and transmit their instrument readings to a satellite that forms part of the communications system. The program aimed to launch 1,250 drifters; that goal was attained on September 18, 2005, with the launch from Halifax, Nova Scotia, of the 1,250th buoy.

The program was conceived by Scripps Distinguished Professor Peter Niiler and is largely led by Niiler and his team at the Scripps Institution of Oceanography at the University of California, San Diego. The GDP forms part of the Global Ocean Observing System and Global Climate Observing System (*see* WORLD CLIMATE PROGRAM) of the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA).

Global Earth Observation System of Systems (**GEOSS**) A program that was agreed on September 16, 2005, by the 61 member countries of the Group on Earth Observations at the Third Observation Summit held in Brussels. GEOSS aims to draw together satellite, balloon, ocean buoy, and surface data from all the world's observation systems. Its headquarters are in the offices of the WORLD METEOROLOGICAL ORGANIZATION (WMO) in Geneva, Switzerland.

The aims of GEOSS are to improve weather forecasting; help prevent and mitigate natural disasters; prevent and reduce environmental damage; and monitor and protect natural resources.

Global Environmental Monitoring System (**GEMS**) An organization that was established in 1975 as part of the EARTHWATCH PROGRAM of the United Nations Environment Programme (UNEP). It was first proposed by a meeting of experts that was convened in 1971 by the organizers of the United Nations Conference on the Human Environment, held in Stockholm, Sweden, in June 1972. The purpose of GEMS is to acquire data pertaining to the natural environment and to make them available to governments and other organizations that need them. The first part of GEMS to be inaugurated was GEMS/AIR, in 1975. It is managed jointly by UNEP and the World Health Organization (WHO).

Global Environment Facility (**GEF**) An international organization that was established in 1990 to provide practical assistance to the environmental improvement programs of governments. The GEF is managed by the World Bank, which controls two-thirds of its funds. The United Nations Environment Programme (UNEP) controls the remaining one-third.

Global Horizontal Sounding Technique (**GHOST**) A project that forms part of the WORLD WEATHER WATCH. GHOST uses balloons for the direct sensing of the atmosphere. The balloons are designed to float at various constant-density levels. Sensors carried beneath the balloons measure TEMPERATURE, HUMIDITY, and AIR PRESSURE. Satellites in polar orbit track the balloons and receive from them data that they transmit to receiving stations.

Global Inventory Monitoring and Modeling Systems (GIMMS) A set of data on global vegetation that are held at the NASA Goddard Space Center. The data are used to produce the NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI), with a resolution of about 4.7 miles (7.6 km).

Global Resource Information Database (GRID) An international organization, based in Geneva, Switzerland, that was established in 1985 by the United Nations Environment Programme (UNEP) and the Swiss Government. It uses computers and software developed by NASA to analyze and integrate environmental information from different sources, including the World Health Organization and the Food and Agriculture Organization.

Global Systems Division (GSD) A division of the Earth System Research Laboratory (ESRL) located in Boulder, Colorado, that is part of the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA). Until October 1, 2005, the GSD was known as the Forecast Systems Laboratory (FSL).

The GSD develops weather forecasting systems and the hardware and software associated with them. It then transfers new technologies to the organizations that will use them.

GSD comprises six divisions: Science; Facility; Demonstration; Systems Development; Aviation; and Modernization. It employs scientists from a number of institutions and scientists doing postdoctoral research are contracted through the National Research Council and the National Center for Atmospheric Research. The GSD is open to the public, and its annual publication *GSD in Review* describes its activities.

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global warming The mean temperature of the atmosphere is increasing throughout the world. From about 1880 until 1940, the atmospheric temperature increased by approximately 0.7°F (0.4°C). The temperature then cooled very slightly until the 1970s, and since the middle 1970s the average rate of temperature rise has been 3.15°F (1.75°C) per century. The early warming, up to 1940, probably represented the final recovery from the LITTLE ICE AGE. Climate scientists estimate that in the course of the 21st century average temperature will rise by 2.2°F–3.4°F (1.2°C–1.9°C). This estimate is based on present observations from surface stations, weather balloons, and satellites and is in broad agreement with estimates from the INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC), which indicate a warming at the surface of 0.3°F (0.18°C) per decade, or 3°F (1.8°C) by 2100. For some years, the readings from surface stations indicated a much more rapid temperature rise than did balloon and satellite measurements. Finally, adjustments brought the different sets of measurements into agreement and it became evident that since the late 1970s, when the first satellite measurements became available, the global average temperature has been increasing by 0.022°F–0.034°F (0.012°C–0.019°C) a year, which is 2.16°F–3.42°F (1.2°C–1.9°C) a century.

Other observations support the fact and extent of the warming. Sea levels are rising by 0.07–0.13 inch (1.9–3.3 mm) a year as seawater becomes warmer and expands, and retreating GLACIERS release water. Data from the network of INTERNATIONAL PHENOLOGICAL GARDENS indicates that the growing season for plants is increasing, as the date of the last spring frost becomes earlier and that of the first autumn frost becomes later.

The warming is not distributed evenly, however. Most of the warming is occurring in the Northern Hemisphere to the north of latitude 30°N, and there is much less warming in the Southern Hemisphere. The strongest warming affects Alaska, northeastern Siberia, and the adjoining part of the Arctic Basin. Average temperatures in the Northern Hemisphere rose by 0.7°F (0.4°C) between 1995 and 2005, suggesting a rise of 7°F (4°C) per century. The Antarctic Peninsula has also warmed strongly, although temperatures are falling over much of the interior of Antarctica. Two-thirds of the global warming occurs in winter and is linked to increased nighttime cloudiness, which inhibits radiational cooling.

Scientists believe that a part of this warming is due to an enhanced GREENHOUSE EFFECT caused by the release into the atmosphere of certain greenhouse gases, principally CARBON DIOXIDE from the burning of fossil fuels. Variations in solar output also contribute, as do natural climate cycles such as the NORTH ATLANtic Oscillation, which controls the thickness and distribution of sea ice in the Arctic Ocean. The relative contributions of each of these remains uncertain, but, based on climate models, most climate scientists consider the greenhouse effect to be the greatest.

Projections of future warming and its consequences are derived from climate models. There are many such models and they are improving constantly, but they are constrained by computing power. They impose a three-dimensional grid over the atmosphere (and in some models the oceans) for modeling purposes, calculating the effects of changes at each point of intersection. Using the world's most powerful and fastest computers, however, the grid is necessarily coarse and unable to process details smaller than the grid scale except by making estimates. This limitation principally affects cloud formation and dissipation, which occur on a more local scale than the model grids can accommodate. There are also limits to the present scientific understanding of atmospheric processes, including those affecting clouds.

Nevertheless, there is widespread agreement among climate scientists that the atmosphere is growing warmer. Although a temperature rise of 3.4°F (1.9°C) is unlikely to prove harmful, the fact that some regions are warming much faster than this while others are barely warming at all makes it difficult to determine the regional consequences.

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***Globigerina* ooze** A sediment, or ooze, that covers most of the floor of the western part of the Indian Ocean, the middle of the Atlantic Ocean, and the equatorial and South Pacific Ocean. It is less extensive elsewhere, but in total it covers about half of the entire ocean floor. At least 30 percent of the sediment consists of the shells (called tests) of tiny ameboid protozoa belonging to the order Foraminiferida and most of these belong to the genus *Globigerina*.

Globigerina species drift at the ocean surface as part of the plankton, but they survive only within certain temperature limits. Each species has its own temperature requirement. Consequently, the species that are found in the sediment can be used to indicate the temperature of the water in which they lived. The presence of *Globigerina menardii* is taken to indicate warm water, for example, and *G. pachyderma* indicates cold water. The tests of some *G. truncatulinoides* coil to the right and those of others coil to the left. The direction of coiling is believed to indicate temperature differences, right coiling indicating warm water and left coiling indicating cold water.

grab sampling A technique for obtaining a sample of air for analysis in which the air is collected very quickly, so that the time taken to obtain the sample is insignificant when compared to the duration of the process or rate of change that is being studied.

gradient wind The wind that flows parallel to the isobars (*see* iso-) at a speed which results from the interplay of the pressure gradient force, the Coriolis effect, and centripetal acceleration. These are the three forces acting around a cyclone or anticyclone.

The pressure gradient force makes air move out of an area of high pressure and into an area of low pressure. As it moves, the air is deflected because of the Coriolis effect. Once it is following a curved path, the air is subject to centripetal acceleration, which is equal to the difference between the pressure gradient force and the Coriolis effect.

Around a center of high pressure, where the tendency is for the air to move outward, the Coriolis effect exceeds the pressure gradient force. This accelerates the wind speed, which becomes supergeostrophic (*see* geostrophic wind). The effect is small, however, for two reasons. The first is that the pressure gradient around a center of high pressure is usually lower than that around a center of low pressure, so the winds are in any case lighter. The second is that the rotation of the Earth is cyclonic, and this acts against anticyclonic flow, slowing it.

Around a center of low pressure, where the tendency is for the air to move inward, the Coriolis effect is weaker than the pressure gradient force. This reduces the wind speed, which becomes subgeostrophic.

The name "gradient wind" refers to the fact that the wind speed is proportional to the pressure gradient. A wind that blows with less force than the gradient wind that would be expected from the pressure gradient and latitude (which determines the magnitude of the Coriolis effect) is said to be a subgradient wind. A supergradient wind is one that is stronger than the gradient wind.

gravitational force The attraction that exists between bodies with a magnitude determined by their masses and that decreases with increasing distance between the bodies according to the INVERSE SQUARE LAW. Gravity is by far the weakest of the fundamental physical forces (the others are the strong and weak nuclear forces and the electromagnetic force), but it is felt on Earth because the Earth is very large. The Earth exerts a gravitational force on a PARCEL OF AIR, and the parcel of air exerts an equal and opposite force on the Earth, although this has no observable effect.

Every body possesses mass. This is measured in pounds or tons and in SI units (*see* APPENDIX IX: SI UNITS AND CONVERSIONS) in kilograms. According to Newton's law of gravitation, the gravitational force (F) between two masses, m_1 and m_2, separated by a distance d, is given by: $F = m_1m_2G/d^2$, where G is the gravitational constant (6.664×10^{-11} N m^2 kg^{-2}).

The gravitational acceleration produced by the Earth's gravitational field is designated by g and has an average value of 32 feet per second per second (9.8 m/s^2). This is the acceleration a body experiences in free fall through a vacuum. The gravitational force acts from the center of the Earth and therefore varies with altitude and latitude, because of the inverse square law. (It varies with latitude, because the Earth is not perfectly spherical and so the distance from the center of the Earth is not everywhere the same.) For most purposes, the value of g can be taken as 32 feet per second per second (9.8 m/s^2).

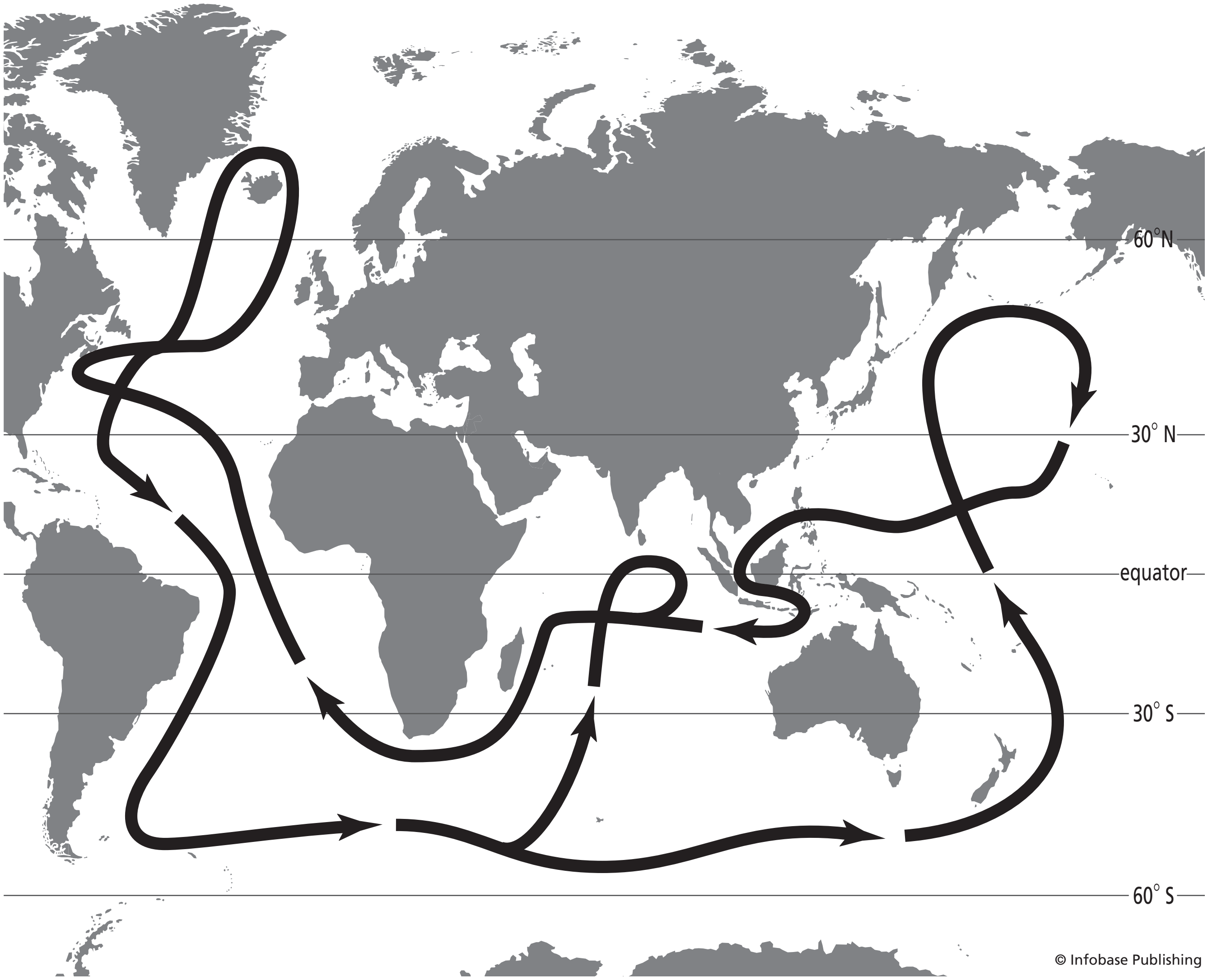
Great Conveyor (Atlantic conveyor) A system of ocean currents that conveys cold water away from the edge of the Arctic Circle in the North Atlantic and warm water from the Pacific through the Indian Ocean and into the Atlantic. The existence of the conveyor was discovered in the 1980s by an American geochemist, Wallace S. Broecker, the Newberry Professor of Geology at Columbia University.

Since the conveyor forms a closed loop, a description of it can begin anywhere, but part of it is driven by the formation of the NORTH ATLANTIC DEEP WATER (NADW). The NADW sinks to the floor of the North Atlantic and flows southward, across the equator and to the edge of the Antarctic Circle, where it joins the West Wind Drift, or Circumpolar Current (*see* APPENDIX IV: OCEAN CURRENTS), flowing from west to east. Part of the current turns north into the Indian Ocean, past the eastern coasts of Africa and Madagascar, and turns south again to the south of Sri Lanka, rejoining the main current.

This diverges from the West Wind Drift to the south of New Zealand, turning northward into the Pacific Ocean and rising to become an intermediate current, flowing about 3,500 feet (1,070 m) below the surface. It crosses the equator, makes a clockwise loop in the North Pacific, then travels westward through the islands of Indonesia, where it crosses the equator once more, across the Indian Ocean, around Africa, and then northward, crossing the equator for the fourth time and returning to the North Atlantic.

The NADW is cold and removes cold water from the North Atlantic. This water remains cold until it rises in the South Pacific. During its progress through equatorial and tropical regions the water warms, and it returns as warm water to the area near Greenland, where it replaces the NADW that is sinking and moving south.

This circulation is of major importance in regulating the climates of the world. It is believed to have failed several times in the past. When it did so, the world experienced climates very different from those of today, when the conveyor is active (*see* YOUNGER DRYAS). Bill Gray, an American meteorologist, has suggested links between the conveyor and climate over the past 125 years. When the conveyor flows strongly, there is an increase in the number of hurricanes (*see* TROPICAL CYCLONE), heavy rainfall in the SAHEL region along the southern edge of the Sahara, few ENSO events, and a general decrease in global mean temperatures. These conditions occurred between 1870 and 1899, and 1943 and 1967. When the conveyor flows weakly, as it did between 1900 and 1942, and 1968 and 1993, there are fewer hurricanes, more ENSO events, rainfall in the Sahel region is average or below average, and global mean temperatures are higher.



The Great Conveyor is a system of ocean currents that carries cold water toward the equator and warm water toward the Poles, strongly influencing climate.

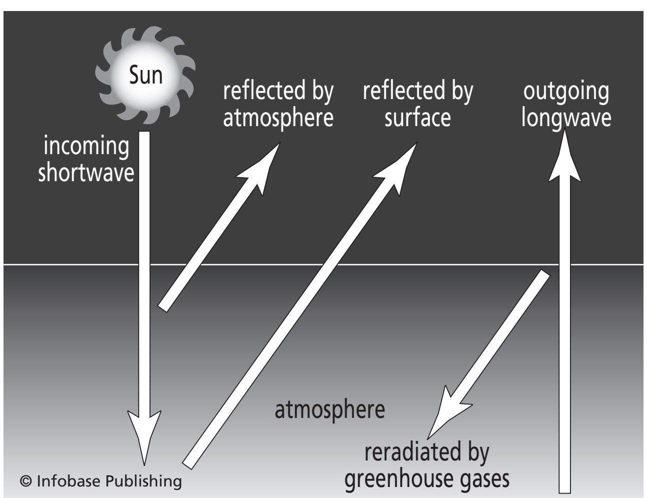
Some scientists fear that a general increase in global temperatures may affect the formation of NADW and trigger a change in the conveyor, causing it to flow more weakly or even to shut down. Were this to happen, it has been suggested that GLOBAL WARMING might induce ice-age conditions in northern Europe. Such an extreme outcome is unlikely, however, because surface ocean currents are driven by the wind and the Gulf Stream would continue to flow even if the conveyor shut down. The North Atlantic Current might no longer break away from the Gulf Stream, so the British Isles and northwestern Europe might no longer benefit from its warm water, but the resultant effect would be quite small and insufficient to offset all of the rise in temperature due to global warming.

greenhouse effect The warming of the atmosphere that is due to the absorption and reradiation of heat by the molecules of certain gases, known as greenhouse gases. Solar radiation is emitted at all wavelengths (*see* SOLAR SPECTRUM). Very short-wave, high-energy, gamma- and X-radiation is absorbed at the top of the atmosphere and does not penetrate it. The shorter wavelengths of ULTRAVIOLET RADIATION are absorbed by atmospheric oxygen (*see* OZONE LAYER).

The radiation that penetrates deeply into the atmosphere is predominantly at wavelengths (*see* WAVE CHARACTERISTICS) between 0.2 μm and 4.0 μm, with a strong peak at 0.5 μm. Visible light is radiation at wavelengths between 0.4 μm (violet) and 0.7 μm (red), the 0.5 μm peak corresponding to blue-green light. Radiation between 0.7 μm and 4.0 μm corresponds to infrared radiation and heat. Of all the radiation Earth receives from the Sun, 9 percent is ultraviolet, 45 percent is visible light, and 46 percent is infrared and heat.

Some of the incoming energy is reflected back into space (*see* ALBEDO) from clouds and from the different surfaces of the land and sea. The remainder is absorbed. The absorbed radiation warms the surface, and as it warms the Earth starts to radiate as a BLACKBODY. This radiation is at much longer wavelengths, between about 5 μm and 50 μm, with a strong peak at about 12 μm.

The gases composing the atmosphere are transparent to incoming solar radiation, but the atmosphere is partly opaque to outgoing long-wave radiation. Certain molecules absorb radiation at wavelengths determined by their own size and shape. Water vapor absorbs radiation at 5.3–7.7 μm and at wavelengths higher than 20 μm, for example, carbon dioxide absorbs at 13.1–16.9 μm, and ozone absorbs at 9.4–9.8 μm. No gas absorbs radiation at 8.5–13.0 μm. This is the atmospheric window through which radiation escapes into space.



The greenhouse effect is the warming of the atmosphere due to the absorption of long-wave radiation by certain gases that are naturally present in the air.

Radiation that is absorbed by gases in the atmosphere is then reradiated by them. This radiation travels in all directions. Some returns to the surface and some is absorbed by other molecules. The overall effect is to retain in the atmosphere more than 90 percent of the heat that is radiated from the Earth's surface. Heat does not accumulate indefinitely, of course (*see* RADIATION BALANCE), but the net effect is to raise the temperature of the atmosphere.

The greenhouse effect makes the atmosphere 54°F–72°F (30°C–40°C) warmer than it would be if the atmosphere were completely transparent to radiation at all wavelengths. Instead of the global mean surface temperature being 59°F (15°C) as it is now, it would be between about 5°F and -13°F (between -15°C and -25°C). This is the figure that is most often used in calculations involving the greenhouse effect.

Some scientists challenge this figure, however, on the ground that it makes an incorrect allowance for the planetary albedo and that it fails to take account of the extent to which heat is absorbed by and reradiated from the uppermost layer of the ocean. Adjustment for the albedo reduces the warming effect to about 36°F (20°C), and when heat retention by the oceans is also taken into account the net warming effect is probably about 25°F (14°C). Without the greenhouse effect, therefore, the mean surface temperature of the atmosphere would be about 34°F (1°C).

This warming through the absorption of radiation by atmospheric gases is what is known as the greenhouse effect. The comparison with a greenhouse is based on the notion that the glass of a greenhouse is transparent to incoming radiation but opaque to outgoing, long-wave radiation, causing the air inside the greenhouse to be warmer than the air outside. The phenomenon is not confined to Earth. It also occurs on all planets with an atmosphere containing greenhouse gases and is most marked in the VENUS ATMOSPHERE.

Many scientists believe human activities that release greenhouse gases may be increasing the natural greenhouse effect and that the resulting enhanced greenhouse effect contributes significantly to the observed GLOBAL WARMING. Depending on the extent of that contribution, the amount of future global warming will be related to the calculated value for the natural greenhouse effect. The critics of this calculation hold that the observed temperature rise (2.6°F–3.42°F; 1.2°C–1.9°C per century) is mainly natural, and that the magnitude of any global warming will be quite small.

The principal greenhouse gases are WATER VAPOR (H_2O), CARBON DIOXIDE (CO_2), nitrous oxide (N_2O; *see* NITROGEN OXIDES), METHANE (CH_4), OZONE (O_3), CFCS, and hydrofluorocarbons. Each gas absorbs at particular wavelengths, and where the wavebands of two or more gases overlap, the amount of absorption is shared between those gases. The amount of radiation absorbed by each gas varies greatly and is reported as its global warming potential. At certain wavelengths, known as the atmospheric window, no outgoing radiation is absorbed.

It is individual gas molecules that absorb the radiation. It imparts energy to them that they then reradiate. Radiation can be absorbed only if it encounters an appropriate molecule in its passage through the atmosphere and into space. The amount of energy absorbed therefore depends on the concentration of those molecules, the higher the concentration the greater being the chance of an impact. It follows that as the atmospheric concentration of a particular greenhouse gas increases, so does the amount of radiation that gas absorbs. Once the concentration reaches a level at which all the radiation at the wavelengths absorbed by that gas is being absorbed, however, adding more of the gas will have no effect. This means there is a limit to the possible magnitude of any greenhouse effect.

Greenhouse gases do not remain in the atmosphere indefinitely. Some cross the tropopause into the stratosphere (*see* ATMOSPHERIC STRUCTURE). The time that elapses between the appearance of a given amount of a greenhouse gas in the troposphere and the appearance of a similar abundance of the same gas in the stratosphere is called the age-of-air.

The amount of CLIMATIC FORCING that a particular greenhouse gas exerts is called the global warming potential (GWP) of that gas. This is compared to the forcing exerted by carbon dioxide, which is given a value of 1. Water vapor, the gas with the strongest greenhouse effect, is not included, because the atmospheric content is highly variable and beyond our control. CFCS have a strong GWP, but these gases are now being phased out under the terms of the Montreal Protocol (*see* APPENDIX V: LAWS, REGULATIONS, AND INTERNATIONAL AGREEMENTS), so in time their influence will decline. GWPs for the remaining greenhouse gases are under constant revision as the scientific techniques for estimating them improve.

GWPs for principal greenhouse gases

Gas	GWP
Carbon dioxide	1
Methane	23
Nitrous oxide	296
HFC-23	12,000
HFC-236fa	9,400
HFC-227ea	3,500
HFC-125	3,400
HFC-134a	1,300
HFC-152a	120
CFC-12	7,100
CFC-11	3,400
Perfluoromethane (CF_4)	5,700
Perfluoroethane (C_2F_6)	11,900
Sulfur hexafluoride (SF_6)	22,200

In the table above, hydrofluorocarbon gases (HFCs) were developed as alternatives to CFCs, because they have no effect on the OZONE LAYER. They are used mainly in refrigeration units and in the manufacture of semiconductors. Perfluorocarbons (PFCs) are also used as alternatives to CFCs in semiconductor manufacture, and they are a by-product of aluminum smelting and uranium enrichment. Sulfur hexafluoride is used as an industrial insulator and in the manufacture of cooling systems for electrical cables.

Further Reading

Department of Energy. "Comparison of Global Warming Potentials" from the Second and Third Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). Department of Energy. Available online. URL: http://www.eia.doe.gov/oiaf/1605/gwp.html. Last updated August 12, 2002.

Greenland Icecore Project (GRIP) A drilling program sponsored by the European Science Foundation that was established to retrieve an ICE CORE 1.86 miles (3 km) long from Summit, the highest point on the GREENLAND ICE SHEET and 17.4 miles (28 km) to the east of the site of the GREENLAND ICE SHEET PROJECT. Analysis of the ice core and of the dust and air trapped in it provided information about the global climate over the past several hundred thousand years.

Drilling began in January 1989 and ended in December 1995. By the end of 1990, the drill had reached a depth of 2,526 feet (770 m), where the ice is 3,840 years old. In 1991, the drill reached 8,270 feet (2,521 m) and ice 40,000 years old, and on August 12, 1992, the drill reached bedrock at a depth of 9,938 feet (3,029 m). Ice at that depth is 200,000 years old. The core is stored, in sections, at the University of Copenhagen, Denmark.

Further Reading

European Science Foundation. "Greenland Icecore Project." European Science Foundation. Available online. URL: www.esf.org/esf_article.php?section=2&domain=3&activity=1&language=0&article=166. Last updated December 11, 2001.

Greenland ice sheet The layer of ice, or GLACIER, that covers 80 percent of the area of Greenland. Beneath the ice sheet, the ground surface is close to sea level over most of central Greenland, but with mountain ranges around the center, parallel with the coast.

The mountains contain the ice, except in a small area in the northwest, close to Qaanaaq (formerly Thule), where the ice reaches the sea, but without forming an ICE SHELF. Ice does reach the sea along valleys through the mountains, the biggest valley glacier being the Ilulissat (formerly Jakobshavn) Glacier on the western coast. This flows at a rate of 66–72 feet (20–22 m) per day at its terminus and is the source of most of the ICEBERGS entering Arctic waters.

The inland ice sheet is almost 1,490 miles (2,400 km) long in a north–south direction and is 680 miles (1,100 km) wide at its widest point, at 77°N. It covers an area of 670,272 square miles (1,736,095 km^2). Smaller ice caps and glaciers cover an additional 18,763 square miles (48,599 km^2). Two north–south domes or ridges, one in the north and the other in the south, are where the ice is thickest. The southern dome is about 9,845 feet (3,000 m) thick at 63–65°N and at about 72°N the northern dome is about 10,795 feet (3,290 m) thick.

The climate over the ice sheet is cold and dry. Mean temperatures fall to -24°F (-31°C) on the north dome and -4°F (-20°C) on the south dome. Precipitation averages about 2.6 inches (67 mm) a year.

In 1993 and 1994, NASA surveyed the entire ice sheet by means of radar ALTIMETERS carried on aircraft. These measured the elevation of the ice surface very accurately. In 1998, the southern part of the ice sheet was surveyed again. This showed three areas where the ice was thickening by more than 4 inches (10 cm) a year, but also large areas of thinning at elevations up to 5,000 feet (1,500 m), especially in the east. The thinning exceeded 3 feet (1 m) a year at the mouth of some outlet glaciers. Above 6,500 feet (2,000 m), the thickness of the ice sheet was not changing, but overall the southern ice sheet was losing ice due to outlet glaciers flowing faster, rather than to warming. More recent measurements have found that when the thickening of the ice sheet is set against the ice being lost from outlet glaciers, the net loss of ice is small.

Further Reading

Greenland Guide Index. Available online. URL: www.greenland-guide.dk/default.htm. Accessed January 17, 2006.

Greenland Ice Sheet Project (GISP) A United States drilling program sponsored by the National Science Foundation (NSF) that retrieved ICE CORES from the GREENLAND ICE SHEET at a site 17.4 miles (28 km) to the west of the European GREENLAND ICECORE PROJECT. The cores are used to obtain information about past climates from analysis of the ice using OXYGEN isotope ratios and from the dust and gas bubbles trapped in it.

The first core reached bedrock, at a depth of about 9,843 feet (3,000 m), and in 1988 the Office of Polar Programs of the NSF authorized the drilling of a second core, GISP2. The drilling of GISP2 was completed on July 1, 1993, when the drill penetrated 5 feet (1.55 m) into bedrock, at a depth of 10,018.34 feet (3,053.44 m). The ice at the base of the ice sheet is about 200,000 years old, and samples of ice at any level can be dated, so the cores provide a continuous climate record that extends over a very long period. When the oldest ice fell as snow over Greenland 200,000 years ago, the Wolstonian Glacial was just beginning. The Wolstonian was the ice age before the most recent (Devensian or Wisconsinian Glacial) and separated from it by the Ipswichian Interglacial (*see* APPENDIX VII: PLIOCENE, PLEISTOCENE, AND HOLOCENE GLACIALS AND INTERGLACIALS).

Further Reading

World Data Center for Paleoclimatology. "Ice Core Gateway Greenland Ice Sheet Project (GISP)." World Data Center for Paleoclimatology. Available online. URL: http://www.ncdc.noaa.gov/paleo/icecore/greenland/gisp/gisp.html. Accessed December 16, 2005.

green taxes Taxation that is levied on the purchase of certain commodities in order to protect the environment by discouraging their use. Taxes are used in preference to banning the use of the commodity in question, because some people or industries have no alternative to using it. This clearly discriminates against certain groups of people and is therefore unfair, but it is argued that manipulating the price encourages more efficient use of the commodity and the development of alternatives. The carbon tax is the best known example. It aims to discourage the use of carbon-based fuels, principally petroleum, but in 2000 it triggered popular protests against the high fuel prices across Europe and in many other countries.

ground heat flux (**soil heat flux**) The flow of heat into the ground by day and upward from the ground at night. Its extent depends on the thermal conductivity (*see* CONDUCTION) of the material composing the ground and the vertical temperature gradient. If these are known, the FLUX can be calculated mathematically, but this is usually impractical because there are too many uncontrolled variables.

The more practical alternative is to measure the flux directly using a heat flux plate. This is a plate made from material with a known thermal conductivity, protected on both sides by thin metal sheets, and equipped with a sensor to measure the temperature difference on either side. The plate is buried horizontally, and the electrical output from its sensor is proportional to the temperature gradient across the plate. The thermal conductivity of the plate should not be greatly different from that of the ground, and the plate should not be so large as to require digging a hole for it that is so big that it disturbs the soil.

groundwater (**phreatic water**) Water that lies below the ground surface in the zone of saturation, also called the phreatic zone, where all the spaces between soil particles are filled with water. The word *phreatic* is from the Greek *phreatos,* which means "well," and it is used because a hole dug from the surface into the phreatic zone will fill with water.

Percolation is the downward movement of water through wet soil until it reaches and joins the groundwater. The movement of water into dry soil is called water infiltration. It is the percolation of water that removes dissolved minerals from the upper layers of soil. The rate at which water will infiltrate dry soil or percolate through wet soil depends on the PERMEABILITY of the soil. A long-term decrease in the amount of surface water and/or groundwater in a region as a consequence of climatic change is called desiccation.

Only about 5 percent of the water that reaches the ground from PRECIPITATION drains downward to join the groundwater. The upper boundary of the zone of saturation is called the water table. Above the water table there is a narrow layer of soil called the capillary layer or capillary zone (*see* AQUIFER), where water is drawn upward by CAPILLARITY. Above the capillary layer the soil is unsaturated. This unsaturated region is called the zone of aeration.

Groundwater may flow horizontally through the soil. The material holding it is then known as an aquifer. The rate of flow varies according to the permeability of the soil. In many soils the groundwater moves through an aquifer from a few feet a day to a few feet a month, but it can move much faster and much more slowly. Water travels at more than one mile per hour (1.6 km/h) through limestone that contains underground cavities, but less than one foot (30 cm) a century through clay or shale.

growing season That part of the year during which the weather allows agricultural and horticultural crops to grow. TEMPERATURE is the limiting factor for plant growth in middle and high latitudes. In the TROPICS and subtropics, where the temperature changes only slightly through the year, the availability of water is the limiting factor. In North America, the growing season is sometimes defined as the period between the last killing frost (*see* FROST) of spring and the first killing frost of autumn.

Identifying the limiting factor describes the conditions in which plants can survive, however, rather than those in which they can grow. Most plant growth ceases when the temperature falls below 43°F (6°C) and so the growing season is also defined as the number of days on which the mean temperature exceeds this value. This is the only definition that is used in Europe. The growing season lasts almost all year at sea level in southwestern England, but for an average 260 days a year at sea level in Scotland. The length of the growing season decreases with elevation above sea level, by about two days for every 100 feet (30 m) in New England, for example.

gust A sudden, substantial increase in the WIND SPEED that lasts for only a short time, after which the wind speed drops to its former level. A gust of wind that produces an almost instantaneous change in the speed or direction of the wind is called a sharp-edged gust. A gust is more short-lived than a SQUALL. Gusts are often caused by EDDIES due to TURBULENT FLOW. They are also generated as a gust front ahead of a storm.

A gust front, also called a pressure jump line, is a region of warm air that lies immediately ahead of an advancing storm. Descending cold air inside the storm cloud pushes forward beneath the warm air, lifting it. This makes the warm air unstable (*see* STABILITY OF AIR). Air rises into the cloud and at the same time starts forming a new convective cell (*see* CONVECTION) ahead of the cloud. Air being drawn into a large, vigorous cloud produces strong, gusty winds.

Gustiness is the quality of a wind that generates frequent gusts, and the gustiness factor is a measure that is used to describe the intensity of the gusts generated by a particular wind. The gustiness factor is calculated by measuring the wind speeds during gusts and during the lulls between gusts to determine the range of wind speeds. The mean wind speed is then calculated across the period in question, including the speeds during gusts and lulls. The gustiness factor is calculated as the ratio of the range of wind speeds to the mean wind speed. This value is taken into account when designing urban developments and forestry plantations.

gyres The major ocean currents (*see* APPENDIX VI: OCEAN CURRENTS) form approximately circular patterns that flow anticyclonically (*see* ANTICYCLONE) in both hemispheres. These circles of moving water, traveling clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, are called *gyres,* which is a word derived from the Greek *guros,* meaning "ring."

Surface ocean currents are driven by the wind. On either side of the equator, the prevailing winds are the trade winds (*see* WIND SYSTEMS), blowing from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. The anticyclonic flow of air around the AZORES HIGH and Bermuda high also drives water in the North Atlantic.

The currents do not flow in the same direction as the wind, however, but form an EKMAN SPIRAL. At the surface, the water moves at an angle of about 45° to the wind, deviating to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The result is that the currents in both hemispheres flow parallel to the equator. The movement of surface water generates differences in pressure between the upper and lower layers of the ocean. These differences cause water below the surface at the base of the Ekman spiral to move in the opposite direction to the surface current.

When they approach continents, the currents are deflected, and as they move farther from the equator, their direction comes under the influence of the CORIOLIS EFFECT. This diverts them farther from the equator. The magnitude of the Coriolis effect increases with latitude, deflecting them still more, and as the currents leave the TROPICS and enter the middle latitudes they are driven by the prevailing westerly winds. The winds drive them toward the east, and the Coriolis effect also deflects them to the east (in both hemispheres). As they approach the continents on the other sides of the oceans, the currents turn back toward the equator.

The North Atlantic gyre begins as the North Equatorial Current. Its name then changes according to the region it traverses. It becomes the Antilles Current and Florida Current before becoming the Gulf Stream. Its southward side is the Canaries Current.

The North Pacific gyre begins as the North Equatorial Current. It moves north as the Kuroshio Current and North Pacific Current and returns to the Tropics as the California Current.

The South Atlantic gyre flows past the eastern coast of South America as the Brazil Current, crosses the Southern Ocean as the Antarctic Circumpolar Current, also called the West Wind Drift, and returns to the Tropics as the Benguela Current.

The South Pacific gyre begins as the South Equatorial Current. It flows southward past the coast of Australia as the East Australian Current, then returns northward as the Peru Current, also known as the Humboldt Current.

The Indian Ocean gyre begins as the South Equatorial Current, flows southward along the African coast as the Agulhas Current, becomes part of the Antarctic Circumpolar Current, and then returns northward as the West Australian Current.

Ocean gyres are BOUNDARY CURRENTS that carry warm water along the western coasts of all the continents except Antarctica and cool water along the eastern coasts. The Gulf Stream appears to be an exception to this rule, but only because the warm side of the current divides into two branches, one of which, the North Atlantic Drift, also called the North Atlantic Current, carries warm water to northwestern Europe. Cool water flows past the western coasts of southern Europe and Africa.

H

Hadean The period, called an eon, in the history of the Earth from the time the Earth formed, 4,567.17 million years ago, until the start of the Archaean eon 3,800 million years ago. The name is derived from Hades, the Greek name for the underworld.

The dating of divisions in the geologic timescale (*see* APPENDIX V) is based on events recorded in the rocks. The Hadean commenced at the formation of the planet, however. This is a date calculated astronomically from the formation of the solar system, and it is not recorded in the rocks—no rocks of that age have been found. Consequently, the Hadean eon is different from all other time divisions and the name is used only informally.

During the Hadean, the Earth was heavily bombarded by rocks entering from space. A solid crust formed and the planet acquired its layered structure, of core, mantle, and crust. The process was interrupted by a collision with a body approximately the size of the planet Mars, which shattered the Earth. As their mutual gravitational attraction drew the molten Earth materials together once more, they formed a pair of bodies, Earth and the Moon. Later in the Hadean the Earth cooled sufficiently for liquid water, acquired from impacting bodies, to condense and form oceans. It was also during the Hadean that Earth acquired its first atmosphere.

hail PRECIPITATION in the form of hailstones, which are hard, more or less spherical pieces of ice. A day on which hail falls is called a hail day.

A column of falling hailstones that is visible beneath the CLOUD BASE is called a hailshaft. A hailswath is an area of ground that is partly covered in fallen hailstones. A strip of ground that is completely covered by fallen hailstones is called a hailstreak. Hailstreaks are seen inside hailswaths.

Many hailstones consist of alternate layers of clear and opaque ice. An individual hailstone begins as a RAINDROP at a low level in the cloud, which is carried upward by a vertical air current. The air temperature inside the cloud decreases with height, and as it rises the raindrop enters a region of the cloud where the air temperature is below freezing. The raindrop freezes, and as an ice pellet it continues to be carried up and down by air currents.

As it travels, the hailstone encounters supercooled water droplets (*see* SUPERCOOLING). Some of these are at a temperature only slightly below freezing. They form a layer of water on the surface of the pellet and then freeze. This produces a layer of clear ice. Other droplets are much colder and freeze instantly on contact with the pellet, forming tiny ICE CRYSTALS with air trapped between them. This produces a layer of spongy, white, opaque ice.

Eventually, the path of the hailstone carries it into a region of the cloud where downcurrents predominate and it is swept downward and out of the cloud. Its size depends on the number of times it has been carried up and down, growing with each cycle by the accumulation of additional layers, and on the vigor of the upcurrents. The hailstone will fall from the cloud when the upcurrents are no longer strong enough to support its weight. In both cases, therefore, the size of the hailstones reflects the size and vigor of the cloud that produced them.

Hailstones range in size from 0.2 inch (0.5 cm) to 2 inches (5 cm)—about the size of a golf ball—but they can be bigger. Hailstones have been known to attain the size of softballs, and one that fell at Coffeyville, Kansas, on September 3, 1970, measured 5.5 inches (14 cm) across and weighed 1.67 pounds (766 g). It is believed to have been traveling at more than 100 MPH (160 km/h) when it hit the ground.

Large hailstones can cause injury and damage to property, breaking windows, including car windows, and roofs. Intense hailstorms can flatten farm crops. Hail is produced only in large cumulonimbus clouds (*see* CLOUD TYPES), and it is associated with violent storms. Storms that generate TORNADOES usually deliver intense falls of hail.

Hail consisting of hailstones that are less than about 0.2 inch (0.5 cm) in diameter (smaller than garden peas), but that are sufficiently solid to remain intact when they hit the ground, is called small hail. These are too small to cause any damage or injury. Small hailstones often consist of a nucleus of graupel surrounded by a layer of clear ice. This gives them a white, frosted appearance. Small hail is often mixed with rain.

Graupel, also known as soft hail or snow pellets, is the name given to precipitation in the form of ice pellets that are soft enough to flatten or smash into fragments when they hit a hard ground surface. The pellets are 0.1–0.2 inch (0.2–0.5 cm) in diameter, but can also be less than 0.04 inch (0.1 cm) across, and most are spherical. They are white and opaque and they form when rime frost accumulates on ice crystals, producing a very loose structure.

Hailstorm damage at Weatherford, Oklahoma, on July 1, 1940 ***(U.S. Weather Bureau)***

A hailstone the size of a baseball that fell in Texas on June 8, 1995 ***(NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory [NSSL])***

The United States is divided into 13 hail regions, which are designated according to the frequency and intensity of the hail they experience. A coded label for each hail region indicates the basic cause of its hail days, the average annual frequency of hail days, the peak season for hail, and the intensity of the hail that falls. The basic cause may be marine (B), macroscale (large) storms (M), or OROGRAPHIC (O)—meaning that storms are caused when air crosses mountains and becomes unstable (*see* STABILITY OF AIR). The peak season may be early (E), late (L), autumn (A), summer (Su), spring (Sp), or winter (W). The intensity may be light (L), moderate (M), or heavy (H). A coded label appears in the form M/2–3/ESu/L. This example indicates that hail is associated with macroscale storms (M), falls on two or three days in an average year (2–3), is most likely in early summer (ESu), and hail falls are light (L).

half-arc angle The angle bisecting the arc that extends from the point directly above the head of an observer (the zenith for that observer) to the horizon seen by the same observer.

half-life The time that elapses while a given quantity is reduced to half its original value. The term can be applied to atmospheric pollutants, but it is most commonly used to describe rates of radioactive decay.

When a radioactive element decays, only the nucleus of the atom is affected. This means that the decay occurs independently of outside chemical or physical conditions and is EXPONENTIAL. The probability that a particular atom will decay in a unit time is called the decay constant, also known as the disintegration constant, and is usually expressed in units of 10^{10} atoms per year. The decay constant for uranium-235 (^{235}U) is 9.72, for example, and that for ^{238}U is 1.54.

It is impossible to predict the lifetime of an individual atom, but simple to calculate how long it takes for half of the atoms in a very large sample to decay. This is the half-life for that element, and it is given by $T = (0.693/\lambda) \times 10^8$, where T is the half-life in years and λ is the decay constant. This calculation reveals that the half-life for ^{235}U is approximately 7.13 million years and the half-life for ^{238}U is 4.5 billion years.

Halogen Occultation Experiment (HALOE) An experiment that is carried on the UPPER ATMOSPHERE RESEARCH SATELLITE. It measures the absorption of infrared radiation (*see* SOLAR SPECTRUM), but only at sunrises and sunsets (occultations). This means it acquires data at only two latitudes each day, but since the satellite is in an inclined orbit (*see* ORBIT) the area it views changes, so eventually it completes a global coverage of the stratosphere (*see* ATMOSPHERIC STRUCTURE). HALOE measures concentrations of a range of gases, including ozone (O_3), nitric oxide (NO), nitrogen dioxide (N_2O), water vapor (H_2O), methane (CH_4), hydrochloric acid (HCl), and hydrogen fluoride (HF).

halophyte A land plant that is adapted to grow in saline soil or salt-laden air. Many coastal plants are halophytes. Glassworts (*Salicornia* species) are halophytes found near seacoasts and in other salt habitats throughout the world, except for Australia.

haze A reduction in VISIBILITY that occurs when AEROSOLS absorb and scatter (*see* SCATTERING) sunlight. Horizontal visibility in a haze does not fall below 1.2 miles (2 km). Usually, the aerosols are large enough to scatter all wavelengths of light. This makes the sky appear white. Not all hazes appear white, however. Some aerosols absorb certain wavelengths (*see* WAVE CHARACTERISTICS) of sunlight but not others. This can give the haze a yellow or brown color. There are also blue hazes, caused by hydrocarbon aerosols emitted by trees and other plants. The particles are so small they scatter blue light but not light at longer wavelengths. Blue hazes have given the Smoky Mountains and the Blue Mountains of Australia their names. Burning fuels and vegetation also releases particles that are small enough to produce haze, and the air over large cities is often hazy. In dry climates, fine dust particles raised by CONVECTION can cause haze. All types of haze are more likely to develop in the still air beneath a temperature INVERSION, where particles accumulate.

The amount of scattering depends on the optical depth (*see* OPTICAL AIR MASS) of the layer containing the aerosols, which depends in turn on the height of the Sun above the horizon. That is why haze is more common early and late in the day than it is in the middle of the day, and why an early morning haze often disappears later. People say the haze has "burned off," but in fact the Sun has risen higher into the sky, reducing the optical depth of the haze layer. Hazes also tend to be thicker when the Sun is low because the aerosols reflect back toward the observer sunlight that was reflected from the ground surface.

A band of haze that is usually seen beneath a temperature INVERSION and that extends to the surface is called a haze layer, and the boundary between the upper surface of a haze layer and the clear air above it is the haze line. The top of a haze layer when seen from above against a clear sky is called a haze horizon. In the distance the upper surface of the haze resembles the true horizon. Despite the resemblance, however, the haze horizon may not be horizontal.

The coefficient of haze (COH) is a measure of the degree of AIR POLLUTION caused by small particles. It is calculated from the proportion of the total amount of light that is transmitted through a filter paper that has been exposed to the air for a specified length of time. The ratio of the brightness of an object seen through haze or FOG to the brightness of the same object seen through clear air is called the haze factor. It is a measure of the extent to which the haze or fog reduces visibility.

If the relative HUMIDITY (RH) is high, water vapor will condense onto haze aerosols. The aerosols absorb the water, which increases their size and makes the haze thicker. The resulting damp haze is a very thin FOG in which visibility does not fall below 1.2 miles (2 km). A haze droplet is a liquid droplet that forms by CONDENSATION onto a HYGROSCOPIC NUCLEUS in air with an RH greater than about 80 percent. The droplets grow and begin to reduce visibility as the RH rises above 90 percent. The droplets are smaller than 1 µm (0.0004 inch) in diameter and remain suspended in the air. Their effect on visibility is too small to be seen in a small volume of air, but they often form a wet haze beneath cumulus clouds (*see* CLOUD TYPES). This is clearly visible to observers on mountains or in aircraft, who have an approximately horizontal line of sight through the haze. If the air reaches supersaturation (*see* HUMIDITY) the haze droplets begin to grow very rapidly. This removes water molecules from the air, sometimes reducing the RH to below supersaturation. Alternatively, the droplets may grow into CLOUD DROPLETS. A haze that contains no water droplets is called a dry haze.

A heat haze is different. This is a shimmer caused by a change in the refractive index of air at different densities and is a type of MIRAGE.

A reduction in horizontal, but not vertical visibility sometimes occurs over the Arctic. This is known as Arctic haze and it extends to a height of more than 30,000 feet (9,150 m).

An ice-crystal haze is one that consists entirely of ICE CRYSTALS. Usually the crystals are being precipitated from a cloud.

A salt haze is a thin haze caused by the condensation of water vapor onto salt crystals when the RH of the air is below about 90 percent. Salt hazes form in humid climates. If the humidity is higher, the haze droplets quickly grow into cloud droplets.

heat capacity (**thermal capacity**) The quantity of heat energy that must be supplied to a substance in order to raise the TEMPERATURE of that substance by a specified amount. It is measured in relation either to a unit mass of the substance, when it is known as the specific heat capacity (symbol c), or to a unit amount of the substance, when it is known as the molar heat capacity (symbol C_m). The heat capacities of gases are given either at constant volume (c_v) or at constant pressure (C_v). In the SI units that are used scientifically (*see* APPENDIX IX: SI UNITS AND CONVERSIONS), heat capacity is reported in joules per gram per kelvin (J/g/K). In the c.g.s. system (*see* UNITS OF MEASUREMENT), heat capacity is reported in calories per gram per degree C (cal/g/°C). 1 J/g/K = 0.239 cal/g/°C; 1 cal/g/°C = 4.187 J/g/K.

Heat capacity varies widely from one substance to another, and water has a higher heat capacity than most common substances, including rock and sand. In the c.g.s. system, the specific heat capacity of water is 1.0 cal/g/°C (4.187 J/g/K). This is an average value, because heat capacity varies slightly with temperature. When stating the heat capacity for a particular substance, it is usual to mention the temperature at which this value applies. For example, at freezing temperature the specific heat capacity of water is 4.2174 J/g/K (1.007 cal/g/°C). At 50°C (122°F) it is 4.1804 J/g/K (0.9985 cal/g/°C), and at 90°C (194°F) it is 4.2048 J/g/K (1.004 cal/g/°C). The table below gives the specific heat capacities of various substances at specified temperatures.

The thermal inertia of a particular material is a measure of the rate at which it responds to a change in the amount of energy it absorbs. Substances with a high heat capacity respond very slowly. Those with a lower heat capacity respond more rapidly. The composition of land surfaces can be inferred from measurements made by REMOTE SENSING of the changes in temperature during the day.

The high heat capacity of water means that it absorbs a large amount of heat with very little change in its temperature. That is why the sea and large lakes warm only slowly during the spring and early summer, despite the warmth of the sunshine and of the air. In

Heat Capacity

Substance	Temp.		*c*	
	°C	°F	J/g/K	cal/g/°C
freshwater	15	59	4.19	1.00
seawater	17	62.6	3.93	0.94
ice	-21–1	-5.8–30.2	2.0–2.1	0.48–0.50
dry air	20	68	1.006	0.2403
basalt	20–100	68–212	0.84–1.00	0.20–0.24
granite	20–100	68–212	0.80–0.84	0.19–0.20
white marble	18	64.4	0.88–0.92	0.21–0.22
quartz	0	32	0.73	0.17
sand	20–100	68–212	0.84	0.20

winter, however, because of the high thermal inertia of water, large bodies of water also cool very slowly and as they do so they release a great deal of heat. If a layer of seawater 3.3 feet (1 m) thick cools by 1.8°F (1°C), the heat that is released is sufficient to warm the layer of air above the sea by 18°F (10°C) up to a height of 33 feet (30 m).

The huge volume of water that is contained in the oceans acts as a major heat store. The oceans absorb heat during the spring and summer and then release it slowly during the autumn and winter. Consequently, AIR MASSES that cross the ocean are warmed in winter and cooled in summer. The high LATENT HEAT of water also contributes to the summer cooling, because of the large amount of heat that is absorbed from the air in order to evaporate water. It is the contrast between the heat capacities of water and of the rock and sand on dry land that produce the marked differences between continental and maritime climates (*see* CONTINENTALITY and OCEANICITY).

Water mixes with sand and other mineral particles and that means the heat capacity of soils varies with their moisture content. Wet soil warms and cools more slowly than dry soil, which is why wet soil or sand feels cold on a warm day, while dry sand can feel very hot. Crop seeds will not germinate below a certain temperature and for this reason, wet weather in spring delays sowing, because farmers must wait until the soil is warm enough.

heat island An area that is markedly warmer than its surroundings and that can therefore be likened to an island of warmth in a sea of cool air. This effect was first described by Luke Howard (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) in *The Climate of London,* published in 1818–19, and it has since been observed in many large cities. It affects all urban areas, but large cities most of all. The effect is patchy, being more extreme in some parts of a city than in others, depending on the kind of activity pursued—industrial or residential, for example—and on the configuration of the buildings and streets. The accumulation of warmth modifies the city atmosphere in a number of ways and produces a distinctive URBAN CLIMATE.

The air temperature in a city rises rapidly during the day and falls again at night. Sometimes the city center is cooler than the countryside at night, but this is unusual. More commonly, the heat-island effect reaches a maximum during the first part of the night, when the difference between the temperature at ground level in the city center and in the surrounding countryside is often 9°F–11°F (5°C–6°C) and can reach 14°F (8°C). The temperature decreases fairly steadily from the city center to the outlying suburbs along a temperature gradient. Once in the countryside, the air temperature remains constant.

When the air is otherwise calm, the heat island often produces a country breeze (*see* WIND SYSTEMS). This is similar to a sea breeze (*see* LAND AND SEA BREEZES).

The heat island results from several causes. Buildings reduce WIND SPEED. The wind blows more slowly the more deeply it penetrates the city, and this reduces its capacity for exchanging air. Consequently, city air that is warmed by mixing with air from heated buildings and industrial operations is replaced infrequently by cooler air. Air is exchanged much more frequently in the open countryside.

The removal of most plants from urban areas reduces the amount of TRANSPIRATION. Where there is an extensive vegetation cover, transpiration absorbs a considerable amount of LATENT HEAT, which cools the air. Trees that line city streets transpire too little moisture to make much difference, but transpiration by the plants in large city parks produces smaller islands of cool temperatures inside the larger heat island.

EVAPORATION is also reduced, because rain and melted snow are carried away rapidly through storm drains, rather than being left to dry by evaporating from exposed water surfaces. In the countryside, some surface water evaporates immediately and some soaks into the ground, but much of the water that sinks from the surface is either drawn upward again by CAPILLARITY or enters plants and is returned to the air by transpiration. Evaporation also absorbs latent heat from the layer of air close to the ground.

Bricks, concrete, stone, and asphalt absorb heat better than the soil, water, and plants of the open countryside (*see* HEAT CAPACITY). They also have a much lower ALBEDO than farmland. A skyscraper absorbs up to six times more heat than a field per unit of surface area. This means city streets and buildings warm quickly during the day and lose their heat just as rapidly at night. The warm surfaces warm the air in contact with them. On a warm summer day the temperature in the city can rise by as much as 31°F (17°C) between dawn and the middle of the afternoon.

Cities also generate heat. Buildings are heated in winter, and in warm climates they are cooled by air conditioners in summer. Heated buildings lose heat through windows and doors to the outside air, and air conditioners work by expelling heated air from the building and replacing it with chilled air. Machines of all kinds warm the air around them and city streets are usually filled with vehicles, all pumping out heated air. A very large urban area, such as Los Angeles or the Boston–Washington megalopolis, generates an amount of heat that is equal to half the solar radiation that falls on a horizontal surface in winter and about 15 percent of the amount that falls in summer.

There are now so many very large cities that heat islands are clearly visible in infrared (*see* SOLAR SPECTRUM) satellite photographs. Many WEATHER STATIONS are located at city airports that have become surrounded by urban development as cities have expanded. They are now within the boundaries of heat islands. Since they are the source of data from which changes in surface temperatures are calculated, some climatologists suspect that, although corrections are made to allow for it, at least some of the reported GLOBAL WARMING may be due to the heat island effect.

Heinrich event The relatively sudden calving of a large swarm of ICEBERGS from North America into the North Atlantic. This is believed to have occurred six times between 70,000 and 16,000 years ago, during the most recent GLACIAL PERIOD. The icebergs, from the LAURENTIDE ICE SHEET, carried rock rubble scraped from the land surface. They drifted eastward, and as they slowly melted the rubble sank to the ocean floor. Fragments of it were found, and their Canadian origin determined by the German oceanographer Hartmut Heinrich, who proposed in 1988 that icebergs had transported them to the northeastern Atlantic, which is where he found them.

Various causes have been proposed for these events. Some scientists suggest the calving resulted from warming, perhaps linked to one of the MILANKOVITCH CYCLES. Others believe it was due to the extent to which the ice sheet thickened during the period of the events. Still others maintain that earthquakes fractured the sheet.

As the icebergs melted, they formed a layer of freshwater floating above the seawater. This is believed to have suppressed the formation of NORTH ATLANTIC DEEP WATER and thus altered or shut down the GREAT CONVEYOR.

heliotropic wind A slight change in the wind direction that takes place during the course of the day and that is caused by the east-to-west progression of the surface area that is most intensely warmed by the Sun.

helium (He) An odorless, colorless, gaseous, nonmetallic element that makes up 0.0005 percent by volume of the atmosphere below a height of 15.5 miles (25 km). Helium is completely chemically inert and forms no known compounds.

Helium is released into the atmosphere through the ALPHA DECAY of radioactive potassium and uranium that are present naturally in rocks. Radioactive potassium (^{40}K) also occurs in all organic matter. Alpha particles, comprising two protons and two neutrons, are the nuclei of helium atoms. Because the air is constantly being mixed, the proportion of helium it contains remains fairly constant throughout most of the atmosphere. The exosphere (*see* ATMOSPHERIC STRUCTURE), however, consists of OXYGEN, HYDROGEN, and helium atoms. About 1 percent of the helium atoms in the exosphere are ionized (*see* ION).

hibernal Pertaining to the winter. The word is derived from *hibernus,* the Latin word for wintry.

hibernation The method by which some mammals and one bird, the poorwill (*Phalaenoptilus nuttalli*), known to the Hopi people as *holchko,* "the sleeping one," survive the winter, when food is very scarce. Most animals that hibernate are no larger than a bat or mouse. Marmots (*Marmota* species) are the largest. They weigh an average 11 pounds (5 kg).

Prior to hibernation, an animal eats voraciously to lay down layers of body fat that will be metabolized gradually through the winter to supply the energy its body needs. The animal then finds a place where it will be safe from predators and where its own body temperature is unlikely to fall below freezing. It makes a nest there and stocks the nest with food that it will need if it should awaken during the winter.

As it enters hibernation, the animal falls into a deep sleep. Its metabolic rate then slows to the minimum needed for survival, typically about 1 percent of the rate when the animal is active. Its rate of breathing slows, its heartbeat slows to about half its nonhibernating rate, its blood vessels constrict, and its body temperature falls, usually to about 40°F (4.5°C). The temperature is maintained at this level throughout the winter, and if it threatens to fall lower the animal awakens and shivers to warm itself. It replaces the energy this uses by feeding on food it stored before entering hibernation.

The change on entering and leaving hibernation is dramatic. In ground squirrels, for example, the first step toward entering hibernation is a drop in the pulse rate from about 200 beats per minute to about 10 beats per minute. Then the temperature falls from 95°F (35°C) to about 39°F (4°C) and the breathing slows from about 100 breaths per minute to about four breaths per minute.

When the weather starts to grow warmer the animal begins to arouse itself. Its heartbeat accelerates, it shivers violently, its breathing accelerates, its blood vessels dilate, and its body temperature rises from 40°F (4.5°C) to 95°F (35°C).

Bears remain inactive through the winter, but they do not hibernate in the true sense of the word. This is because a bear could not generate the energy it would need to arouse itself from hibernation. If a bear weighing 440 pounds (200 kg) were to hibernate, allowing its temperature to fall from its normal 100°F (38°C) to 40°F (4°C), warming itself to leave hibernation would take several days and require as much energy as the bear uses in approximately 3.5 days of ordinary activity. It would be impossible for the bear to eat sufficient food prior to hibernation for it to deposit a layer of body fat that was thick enough to sustain it through the winter and then allow it to revive.

Certain species of swifts (family Apodidae), swallows (family Hirundinidae), nightjars (family Caprimulgidae), and hummingbirds (family Trochilidae) enter a state of torpor in very cold weather. The birds may appear to be dead and may remain so for several days. At one time this led some naturalists to suppose that these birds hibernate. Their torpor is not true hibernation, however.

Further Reading

Allaby, Michael. *Deserts*. New York: Facts On File, 2001.

high An area in which the surface AIR PRESSURE is higher than the air pressure in the surrounding area. The term refers only to horizontal comparisons of pressure and not to differences in pressure at varying heights above each other, and the term most commonly refers to the situation at sea level. Comparisons can be made at any height above the surface, however, provided the pressures being compared are measured at the same height. Thus it would be correct to speak of a high at a particular height, although this use of the term is unusual.

The term also refers to measurements taken at the same time and not to variations in air pressure in the same place but at different times.

Air circulates anticyclonically around a high, and *high* is often used interchangeably with ANTICYCLONE, although the two words are not synonymous (*see also* LOW).

Holocene epoch **(Postglacial, Recent)** The geologic time (*see* APPENDIX V: GEOLOGIC TIMESCALE) in which we are now living. It commenced about 10,000 years ago, which is when the most recent (Wisconsinian) GLACIAL PERIOD ended. The Holocene follows the PLEISTOCENE EPOCH and the two together make up the PLEISTOGENE PERIOD of the CENOZOIC era.

The history of the Holocene has been reconstructed by the study of POLLEN found in layers of soil that can be dated and is divided into five ages: the Pre-Boreal; Boreal; Atlantic; Sub-Boreal; and Sub-Atlantic periods.

The Pre-Boreal period lasted from about 10,300 years ago until about 9,600 years ago and was a time when forests were expanding rapidly. In central North America there were spruce forests in the north and broad-leaved forests farther south. Birch and pine forests replaced tundra in Europe.

The Boreal period lasted from about 9,600 to 7,500 years ago, immediately prior to the Atlantic period. During the Boreal, the climate of northwestern Europe was drier and more continental (*see* CLIMATE TYPES) than it is today, but it was also becoming steadily warmer. It was the last period since the end of the most recent glacial period during which Britain was linked to mainland Europe by a land bridge across the Dover Strait.

The Atlantic period lasted from about 7,500 to 5,000 years ago, following the Boreal period. During the Atlantic period the climate of northwestern Europe was moist, and warmer than it has been at any time since.

The Sub-Boreal period lasted from about 5,000 years ago until 2,800 years ago and was a time of a colder, drier, more continental climate than the preceding Atlantic period, although summers were warmer than those of today.

The Sub-Atlantic period began approximately 2,800 years ago, at about the time Iron Age cultures replaced those of the Bronze Age, and it is the period in which we are living today. Summers became cooler and climates became generally wetter than those of the preceding Sub-Boreal period.

There have been significant climatic fluctuations within the Sub-Atlantic period. A MEDIEVAL WARM PERIOD was followed by the LITTLE ICE AGE, which ended gradually during the latter part of the 19th century. During the 20th century, climates grew markedly warmer until 1940, then cooler again until the 1970s, after which they remained fairly constant until the 1980s, since when they have increased.

All Holocene climates are warmer than those of the Pleistocene, but the present epoch has continued for only about the length of one of the Pleistocene INTERGLACIALS. Despite concerns about GLOBAL WARMING, it is likely that we are living in an interglacial that will be followed by a new ice age. If that is so, it may be that we are really living in a Pleistocene interglacial, and the use of the term *Holocene* should be abandoned.

humidification The deliberate addition of moisture to the air in order to increase its HUMIDITY, often with the aim of reducing the accumulation of STATIC ELECTRICITY.

A device that injects moisture into the air is known as a humidifier. It works by bringing the air into contact with water, with the air and water both at the same temperature. If necessary, the air is warmed or cooled to bring it to the temperature of the water. Humidifiers are often fitted to air conditioning or central heating systems. The operation of a humidifier is controlled by a humidistat, which monitors the humidity of the air, bringing air and water into contact only when the humidity is low.

Some humidifiers incorporate a dehumidifier, which removes moisture by bringing the air into contact with very cold water, causing some water vapor to condense, or by passing the moist air over a bed of hygroscopic crystals.

humidity The amount of WATER VAPOR that is present in the air—the "wetness" or "dryness" of the air. The term refers only to water that is present as a gas; CLOUDS, which are composed of ICE CRYSTALS or liquid droplets of water, and PRECIPITATION falling through the air do not count in the measurement of humidity.

Humidity can be measured in several ways: as the mixing ratio, specific humidity, absolute humidity, and by the most widely used measure of all, as relative humidity. When weather reports state the humidity, relative humidity is usually what they mean. The instruments that measure humidity are known as HYGROMETERS.

The mixing ratio, also called the mass mixing ratio, is the ratio of the mass of any particular gas present in the air to a unit mass of dry air. This is usually measured as grams of the gas in one kilogram of air without the gas. It is most often used to refer to the amount of water vapor present, as grams of water vapor in one kilogram of dry air: grams H_2O/kg air. Because it is measured in units of mass, it is not affected by changes of TEMPERATURE or pressure, unlike absolute humidity. The mixing ratio of water vapor is difficult to measure directly, but it can be determined from the relative humidity. Mixing ratio should not be confused with specific humidity.

The specific humidity is the ratio of the mass of water vapor that is present in the air to a unit mass of that air including the water vapor. It is usually measured as grams of water vapor in one kilogram of air that includes the water vapor. Specific humidity is calculated differently from the mixing ratio, but for most practical purposes the two are identical. This is because the amount of water vapor present is rarely more than a very small proportion of the total mass of air, so whether or not it is included in the unit mass of air used for the calculation makes little difference to the outcome. The ratio of the actual specific humidity of a body of air to the specific humidity of saturated air at the same temperature and pressure is called the *saturation ratio*.

The psychometric equation is used to calculate the specific humidity of air from the wet-bulb temperature and dry-bulb temperature (*see* THERMOMETER) registered by a psychrometer (*see* PSYCHOMETRY). The equation is:

$$q(T) = q_s(T_w) - \lambda(T - T_w)$$

where $q(T)$ is the specific humidity of the air, $q_s(T_w)$ is the saturated specific humidity of the air, T is the dry-bulb temperature, T_w is the wet-bulb temperature, and λ is the psychrometric constant. The psychometric constant is equal to C_p/L, where C_p is the specific heat of air (*see* HEAT CAPACITY) and L is the LATENT HEAT of vaporization of water. The value of the psychrometric constant varies according to the temperature and atmospheric pressure. At 68°F (20°C) and a pressure of 14 pounds per square inch (100 kPa) it is 0.0009 ounce per cubic foot per degree F (0.489 g/m^3/K). The psychrometric equation can be converted to calculate the vapor pressure or vapor density of the air.

Absolute humidity is the mass of the water vapor that is present in a given volume of air. It is usually expressed in grams per cubic meter (1 g/m^3 = 0.046 ounce per cubic yard). This measure takes no account of the fact that changes in pressure and temperature alter the volume of the air, which changes the absolute humidity without involving the addition or removal of any moisture. For this reason absolute humidity is not a very useful measure and is rarely used.

Relative humidity (RH) is the ratio of the mass of water vapor that is present in a unit mass of dry air (the mixing ratio) to the amount that would be required to produce saturation (the saturation mixing ratio) in that air. It is written as a percentage and can be expressed as:

$$\text{RH} = (\text{mixing ratio} \div \text{saturation mixing ratio}) \times 100.$$

RH is the measure of humidity that is most frequently used, and the one that is quoted in weather reports. This is because it tells us what is important about the humidity from a meteorological point of view—how close the air is to saturation and, therefore, the likelihood that clouds will form or that precipitation will fall.

RH is also easily misunderstood, because it gives no direct indication of the actual quantity of water vapor present. This is because the moisture-holding capacity of the air varies with the temperature. Warm air can hold much more water vapor than cool air and yet have a much lower relative humidity. On a January day in Boston, Massachusetts, for example, the temperature might be 36°F (2°C) and the RH 63 percent. On the same day at Phoenix, Arizona, the temperature might be 65°F (18°C) and the RH 40 percent. It seems as though the air over Boston contains more moisture (RH 63 percent) than the air over Phoenix (RH 40 percent). In fact, though, the reverse is true. Owing to the fact that the air in Phoenix is warmer than the air in Boston, each cubic yard of the Boston air contains 0.16 ounce of water vapor (3.5 g/m^3) whereas each cubic yard of Phoenix air contains 0.28 ounce (6.1 g/m^3).

Its dependence on temperature is also the major disadvantage of RH to atmospheric scientists. RH does not yield values from which the moisture content of the air over different places or over the same place at different times can easily be compared.

RH is measured directly, using a hair HYGROMETER, or more accurately by using a psychrometer to determine the wet-bulb depression (*see* THERMOMETER). The RH is then read from a table containing RH values calculated from the dry-bulb temperature and wet-bulb depression. A hygrogram is a chart that shows a continuous record of the RH of the air over a period, usually of one week, as this is measured by a type of hygrometer known as a hygrograph.

Supersaturation is the condition of air in which the RH exceeds 100 percent. The RH of air inside clouds is usually between 100 percent and 101 percent, so the supersaturation is said to be between 0 and 1 percent (= RH - 100). Supersaturation occurs because water vapor condenses only with difficulty in the absence of CLOUD CONDENSATION NUCLEI, due to the THOMSON EFFECT.

The amount of water vapor air can hold varies according to the temperature—the warmer the air, the more water vapor it is able to hold. At 59°F (15°C), for example, which is the mean temperature over the entire surface of the Earth, air can hold as much water vapor as produces 17 mb of pressure. When the temperature rises to 95°F (35°C), the amount of water vapor the air can contain increases to a SATURATION VAPOR PRESSURE of 50 mb. At 14°F (-10°C) it can hold only 2.6 mb. As proportions of sea-level atmospheric pressure, these are 1.7 percent, 4.9 percent, and 0.26 percent, respectively. These examples of saturation vapor pressure demonstrate that water vapor is never more than a minor constituent of the air and that the amount is very variable. It is not included in lists of the ingredients making up the air, because the amount varies from place to place and from hour to hour.

Air temperature decreases with height, which means that the moisture-holding capacity of the air also decreases with height. Because of this, most of the water vapor in the atmosphere is contained in the air below about 18,000 feet (5,500 m).

Water vapor can also be measured as precipitable water, which is the depth to which an area of the

Saturation mixing ratio

Temperature °F (°C)	Saturation mixing ratio g/kg
104 (40)	47
95 (35)	35
86 (30)	26.5
77 (25)	20
68 (20)	14
59 (15)	10
50 (10)	7
41 (5)	5
32 (0)	3.5
14 (-10)	2
-4 (-20)	0.75
-22 (-30)	0.3
-40 (-40)	0.1

ground surface would be covered by rainwater if all the water vapor in the column of air above that area were converted to rain. The amount is surprisingly small. Over southern Asia, during the MONSOON, the air holds no more than about 2.5 inches (64 mm) of rain, accounting for about 7 percent of the air by weight. Air over a low-latitude desert holds about 0.5 inch (10 mm), and air over central Antarctica often holds no more than one-tenth of that amount (by weight about 2 percent and 0.2 percent, respectively).

Water enters the air by EVAPORATION and TRANSPIRATION. Evaporation reaches a maximum during the day, but may continue at a reduced rate through the night. This means the movement of water vapor in the air is predominantly upward, moist air being carried aloft mainly by EDDIES. As it rises, drier air descends from higher levels, diluting it. Moisture returns to the surface by precipitation.

Air in which the RH is higher than is usual for the place and season in which it is experienced is called damp air. In Minneapolis, Minnesota, for example, the average RH at noon in July is 52 percent. If the humidity reached 70 percent, people would think the air was damp. In Seattle, Washington, in contrast, the average RH at noon in July is 68 percent and a 70 percent RH would feel quite normal.

Air in which the RH is 100 percent is said to be saturated. Saturation does not refer to the actual amount of moisture present in the air, but only to the amount present as a percentage of the greatest amount air at a particular temperature can hold at that temperature. The saturation mixing ratio is the value of the mixing ratio of saturated air at a particular temperature and pressure. The table at left shows variations in the saturation mixing ratio with temperature at mean sea-level pressure.

hydrogen (**H**) The lightest element, and the most abundant in the universe. A hydrogen atom comprises one proton and one electron. Its atomic number is 1, relative atomic mass 1.00794, melting point -434.45°F (-259.14°C), and boiling point -423.17°F (-252.87°C). It is a colorless, odorless gas.

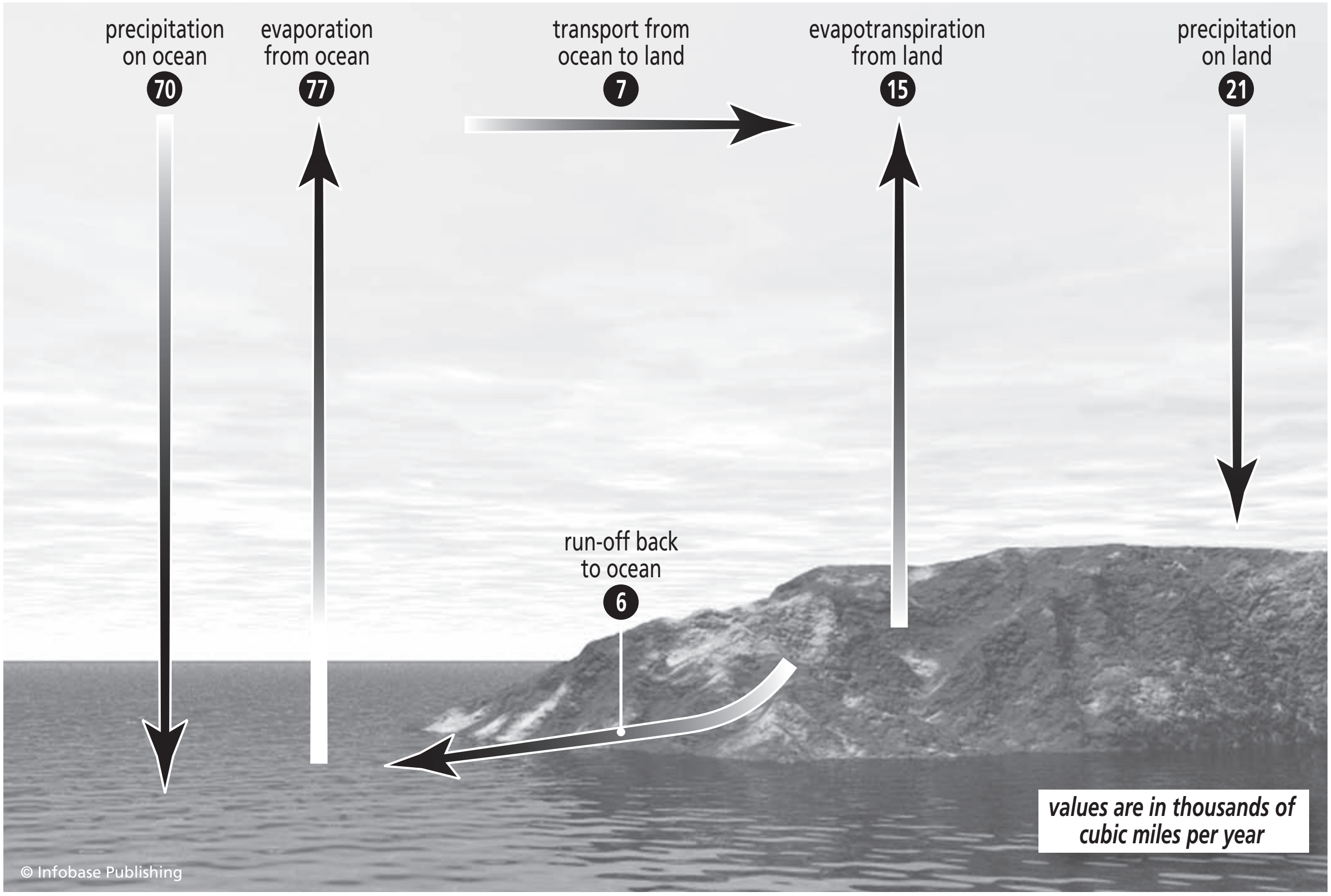
Hydrogen occurs naturally as two ISOTOPES. Hydrogen-1 accounts for 99.985 percent of hydrogen. The remainder is deuterium (D), or heavy hydrogen (relative atomic mass 2.0144) in which the nucleus comprises one proton and one neutron. Deuterium oxide (D_2O) is heavy water. A third isotope, tritium (T), is made artificially. A tritium nucleus has one proton and 2 neutrons. It is radioactive, with a half-life of 12.3 years, undergoing beta decay to helium-3.

Water is dihydrogen oxide, and hydrogen is present in all organic compounds. It burns readily, and is often proposed as an alternative fuel to gasoline for driving vehicles, because the only combustion product is water ($2H_2 + O_2 \rightarrow 2H_2O$ + heat).

hydrological cycle (**water cycle**) The constant circulation of water from the oceans to the atmosphere and back to the surface as PRECIPITATION. There is a total of about 0.33 billion cubic miles (1.36 km^3) of water on Earth, of which about 3 percent exists as FRESHWATER, and about 75 percent of all the freshwater on

Freshwater distribution

Location	Percent of total freshwater
icecaps and glaciers	75
ground water	22
upper soil	1.75
lakes and inland seas	0.6
rivers	0.003



Water enters the air by evaporation and evapotranspiration and returns to the surface as precipitation. A small amount is transported from the oceans to the land through the air, and rivers carry the same amount from the land back to the sea. (Numbers do not add up precisely because of rounding.)

Earth is held in the polar icecaps and GLACIERS. The table sets out the way the freshwater is distributed.

The small amount of freshwater that exists in the liquid phase must satisfy all the needs of organisms that live on land and in freshwater lakes and rivers. This water is transported through the atmosphere and the amount present in the atmosphere at any given time is approximately 3,120 cubic miles (13,000 km^3), which is about 0.03 percent of the total amount of freshwater and about 0.001 percent of all the water on the planet.

Each year about 77,000 cubic miles (321,000 km^3) of water evaporates from the oceans and about 15,000 cubic miles (62,500 km^3) leaves the land by EVAPOTRANSPIRATION, so a total of 92,000 cubic miles (383,500 km^3) of water enters the atmosphere as WATER VAPOR. Of the total amount of water evaporating from the oceans, about 7,000 cubic miles (29,000 km^3) is carried by the air from the oceans to the land. The remainder, of about 70,000 cubic miles (291,600 km^3) condenses and falls back into the ocean as precipitation. About 21,000 cubic miles (87,500 km^3) falls as precipitation over land. This leaves a balance of 6,000 cubic miles (25,000 km^3), which is the amount of water that is carried by rivers from the land back to the sea.

It is EVAPORATION that injects water vapor into the atmosphere, the CONDENSATION of water vapor that produces CLOUDS, and clouds that produce precipitation. Although the amount of water present in the air as vapor, liquid droplets, hailstones, ice crystals, and snowflakes represents only a tiny proportion of the total amount of water on the Earth, it is nevertheless involved in most of the processes that generate our weather. The hydrological cycle, or water cycle, is what produces most of our weather.

hydrosphere Water that is present at or close to the surface of the Earth. The term includes the oceans, icecaps, lakes, and rivers, and also GROUNDWATER. The hydrosphere is contrasted with the atmosphere, which is the gaseous envelope surrounding the Earth, and the lithosphere, which is the solid surface of the Earth.

hydrostatic equation A mathematical equation that relates the weight of a column of air to the pressure exerted on it from above, at height p_2, and from below, at height p_1. If the weight of a PARCEL OF AIR is exactly balanced by an upward pressure at its base, the column of air is said to be in hydrostatic equilibrium. If a parcel of air sinks under its own weight, it will compress the air beneath it. This will increase the upward pressure exerted by the air beneath the parcel until that upward pressure is equal to the weight of the parcel. Its descent is then halted, and the parcel of air is in hydrostatic equilibrium. The hydrostatic equation describes the circumstances leading to hydrostatic equilibrium. The assumption that the atmosphere is in hydrostatic equilibrium is called the hydrostatic approximation.

The cross-sectional area of the column of air is taken to be 1. The weight of the air is equal to its mass (M) multiplied by its gravitational acceleration (g). The equation is then:

$$M\,g = p_1 - p_2$$

This assumes that the DENSITY of the air remains constant throughout the column and that the gravitational acceleration is a constant. The density remains almost constant for a shallow column, but for a deeper column allowance must be made for the reduction in air density due to the vertical pressure gradient. This produces a differential equation:

$$\delta p/\delta z = -g\rho$$

where p is pressure, z is height, ρ is density, and the minus sign indicates that density decreases with height.

Gravitational acceleration decreases with height according to the INVERSE SQUARE LAW, but within the troposphere (*see* ATMOSPHERIC STRUCTURE) the effect is so small that it may be ignored. Gravitational acceleration also changes with latitude, and by an amount large enough to be significant in some calculations. To allow for this, GEOPOTENTIAL HEIGHT is used rather than vertical distance (geometric height).

Using the hydrostatic equation as the vertical EQUATION OF MOTION produces a quasi-hydrostatic approximation. This assumes that there is some vertical motion of air, but that it is small.

hydroxyl A hydroxide molecule, which consists of one oxygen atom bonded to one hydrogen atom (OH). It is produced mainly by the action of ULTRAVIOLET RADIATION on OZONE in the presence of water molecules.

$$O_3 \rightarrow O_2 + O$$

$$O + H_2O \rightarrow 2OH$$

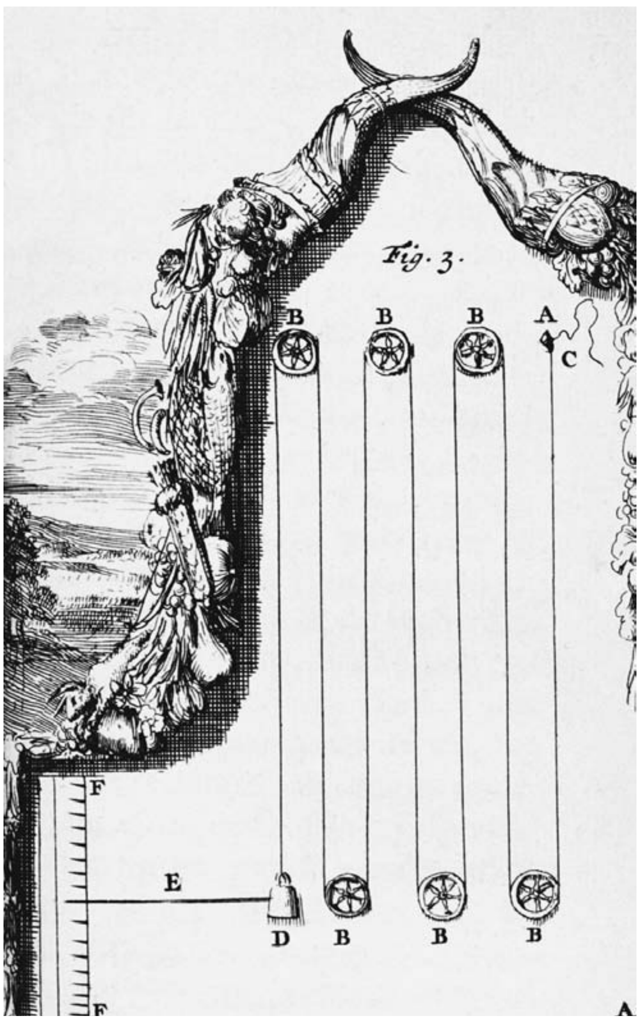
Hydroxyl carries a negative charge (indicated as OH^-) and is known as a free radical. It is extremely reactive. METHANE and many chemical pollutants are removed from the air by reactions with hydroxyl that yield harmless or soluble products. Methane, for example, reacts to form CARBON DIOXIDE and WATER.

hygrometer An instrument that measures the HUMIDITY of the air. There are several types. The hair hygrometer is the one most often used domestically. It is the cheapest and gives a direct reading without requiring calculations. There is also the dew cell, which measures dew point temperature (*see* DEW), and the resistance hygrometer, which is the instrument most often used in radiosondes (*see* WEATHER BALLOON) and weather satellites. Meteorologists often use the psychrometer (*see* PSYCHROMETRY), which is more accurate.

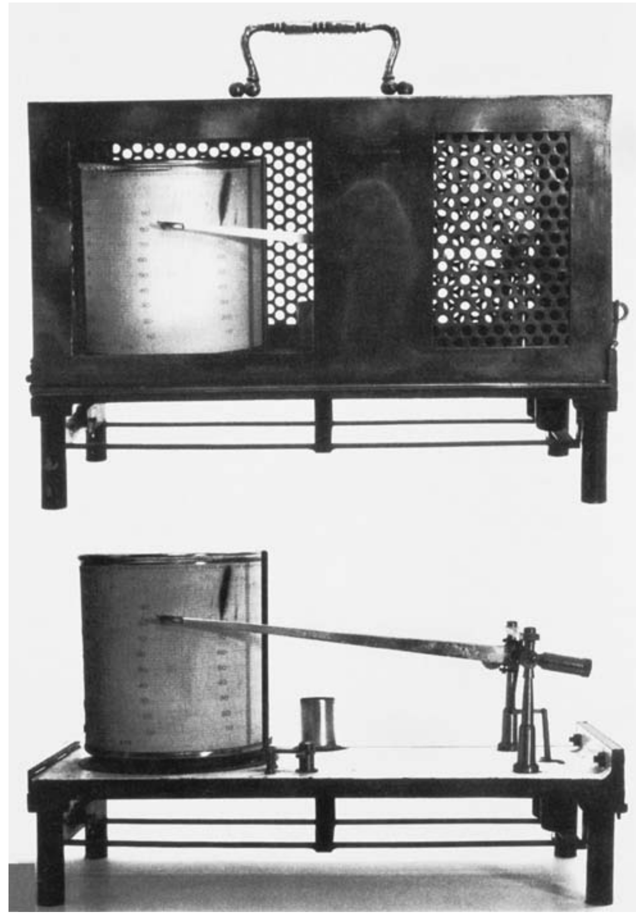
A hygrograph is a type of hygrometer in which changes in the relative humidity of the air cause a pen to rise or fall, tracing a line on a chart that is fixed to a rotating drum. The resulting record is known as a hygrogram.

The hair hygrometer, also called the hygroscope, measures atmospheric humidity and gives a direct reading of the relative humidity (RH). It is the commonest type of hygrometer for domestic use. The hair hygrometer exploits the fact that the length of a human hair varies according to the humidity. As the humidity increases, hairs lengthen, and they shrink as the humidity falls. This is a characteristic derived from the physical structure of the hair, and it remains constant for a particular hair, at 2 percent to 2.5 percent for a change from RH 0 percent to RH 100 percent. The instrument contains a bundle of hairs that are wound around a drum and linked mechanically to a pointer on a dial. Each instrument is calibrated individually to take account of the particular characteristics of the hairs used.

The weather house is a household ornament that claims to predict the weather. It consists of a house with two doors and the figure of a person—usually a man and a woman or a young woman and an old woman—behind each. Only one figure at a time can emerge through its door. When one of the figures emerges it is supposed to mean rain is imminent, and when the other figure emerges the weather is supposed to remain fine. In fact, the device is a hair hygrometer. The figures are made to move by the contraction or stretching of one or two lengths of hair in response to the humidity.



An antique hair hygrometer, from an illustration in a French book, *Traittez de barometers, thermometres, et notiometres, or hygrometres* by Joachim d'Alence, published in 1688. A hair attached at point A is wound round several pulleys (B) and held in tension by a weight (D) to which a pointer is attached. As the length of the hair increases and decreases with changing humidity the pointer moves against the scale. *(NOAA Library Collection)*



A hygrometer register, built to record variations in relative humidity. The precise age of this instrument is unknown. *(Y. Berard, NOAA Ship Collection)*

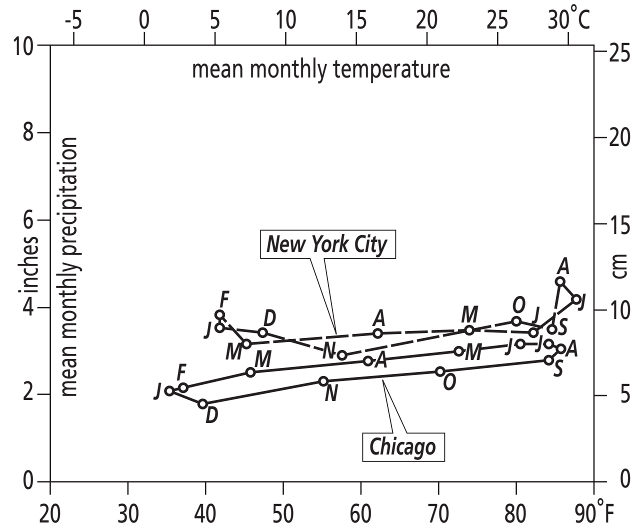
A dew cell or dew point hygrometer measures the dew point temperature directly. It has a mirrored surface that is cooled electrically. As soon as water starts condensing onto it, the reflectance of the surface changes. This change is detected by a photoelectric sensor, which trips a switch, causing the mirrored surface to be heated. As soon as the water evaporates from the surface the change in reflectance is once again detected, and the cooling circuit is activated. This alternation between heating and cooling continues until the two stabilize. The TEMPERATURE at which this happens is the dew point temperature, and its value appears on the display.

A resistance hygrometer measures relative humidity directly, with an accuracy of ± 10 percent. It exploits the fact that the electrical resistance of certain materials, such as carbon black, changes with variations in the relative humidity. An electrical conductor is coated with the material, and changes in the current flow are measured. Because radiosondes and satellites measure temperature at the same time as they measure relative humidity, other types of humidity values can be calculated from resistance-hygrometer data. Owing to the widespread reliance on radiosonde and satellite measurements, this is now the most widely used type of hygrometer.

hygrophyte A plant that grows in wet places or in very humid climates.

hygrothermograph An instrument that provides a continuous record of both relative HUMIDITY and TEMPERATURE. It consists of a THERMOGRAPH and HYGROGRAPH, each connected to a separate pen.

hythergraph A diagram that allows the climates of two or more places to be compared at a glance. Mean TEMPERATURE is plotted against the vertical axis and mean PRECIPITATION against the horizontal axis. The values are plotted for each month and joined by straight lines, ending with the point for December linking to that for January, thus producing a closed figure of irregular shape. The shape and dimensions of the figure indicate



A hythergraph is a diagram that allows the climates of different places to be compared easily. In this example, New York and Chicago are compared. The position of the closed loop produced for each city by joining the points for each month shows whether one city is colder or wetter than the other.

the range of temperature and precipitation experienced through the year and the location of the figure indicates the overall temperature and precipitation.

A hythergraph for New York City and Chicago, for example, reveals that while both cities enjoy about the same summer temperatures, Chicago has slightly colder winters, and New York City has the wetter climate. The word is from the Greek words *hyetos,* meaning “rain,” and *thermos,* meaning “temperature.”

I

ice The solid phase of WATER, in which the water molecules are arranged in a regular, repeating lattice, with each molecule linked to its neighbors by hydrogen bonds (*see* CHEMICAL BONDS). Pure freshwater freezes at 32°F (0°C); seawater at 35 per mil salinity freezes at 28.56°F (-1.91°C).

When water freezes (*see* FREEZING), substances dissolved in the water are forced out of solution. Traces of concentrated solution may be trapped in spaces between ICE CRYSTALS, but the ice consists of pure water.

Hydrogen bonding produces an open lattice structure. Consequently, at standard sea-level AIR PRESSURE water reaches its maximum density while still in the liquid phase, at 39.2°F (4°C) for freshwater and 32°F (0°C) for seawater at a salinity of 35 per mil. As water freezes, therefore, it also expands.

The ice lattice is disordered at the surface of a mass of ice, because there are fewer hydrogen bonds at the surface to hold the water molecules in place. Molecules that are more loosely held project above the ice surface and vibrate more vigorously than those inside the lattice. A surface layer, just a few molecules deep, is able to move like a liquid despite being at a temperature well below freezing. This is called surface melting and it is what makes ice slippery.

Ice melts when its temperature rises above 32°F (0°C), provided the atmospheric pressure is 14.7 pounds per square inch (equal to 29.9 inches (760 mm) of mercury, 101.325 kPa, and 1013.25 mb). A change in pressure alters the freezing temperature. The melting of ice that is subjected to a strong pressure is called pressure melting. As the pressure increases, the freezing temperature of water decreases by approximately 1°F for every 95.5 pounds per square inch increase in pressure (1°C for every 14 MPa). The weight of ice in a temperate GLACIER exerts sufficient pressure to melt a thin layer of ice at the base. The temperature at which ice begins to melt under a given pressure is known as the pressure melting point.

Black ice, also called glaze and clear ice, is a solid layer of ice up to one inch (2.5 cm) thick that forms on roads, radio and television masts, the superstructure of ships, and similar exposed surfaces. It accumulates when rain that is close to freezing or supercooled (*see* SUPERCOOLING) falls onto surfaces that are at or below freezing temperature. The water droplets spread on impact, forming a thin layer that then freezes. This results in a fairly even covering of ice. The ice is transparent, hence the names black ice, glaze, and clear ice, and it may be difficult to see. Black ice on roads produces extremely hazardous driving conditions. The weight of ice that forms in an ICE STORM can be enough to break branches from trees and bring down power lines.

The breakup of river ice that occurs in spring in Eurasia and North America is called a débâcle. It begins in March in the south and progressively later farther north.

iceberg An iceberg is a large block of ice, floating in the sea, which has broken away from the edge of an ICE SHELF or the outlet of a GLACIER. The breaking of a large mass of ice from the edge of a glacier or ice shelf is called calving. The ice that breaks free moves away over the sea. Approximately 10,000 icebergs with a total volume of 67 cubic miles (280 km^3) are released each year into arctic waters. Far more, with a total volume of about 430 cubic miles (1,800 km^3) enter Antarctic waters.

Most arctic icebergs originate in western Greenland and some in eastern Greenland and Franz Josef Land, where valley glaciers enter the sea. They are often about 150 feet (46 m) tall and 55 feet (180 m) long. A growler is a small piece of an iceberg, less than about 33 feet (10 m) long. It floats low in the water, and its surface is often pitted. Although they are small, growlers can cause considerable damage to any ship that collides with one. A bergy bit is bigger than a growler but smaller than an iceberg. A fragment of an iceberg that has an irregular surface, a surface area of up to 200 square miles (520 km^2) or more, and that is 50–150 feet (15–45 m) thick is called an ice island.

Because they are derived from glaciers that have crossed land from which they acquire sediment and stones, arctic icebergs are usually dark in color. The oldest and hardest glacier ice is slightly blue or green in color. It is called blue ice.

Antarctic icebergs break away (calve) from the edge of the ice shelves. They are of similar average height to arctic icebergs, but often 5 miles (8 km) or more—sometimes much more—in length. In 1998, an iceberg 92 miles (148 km) long and 30 miles (48 km) wide broke away from the Ronne-Filchner Ice Shelf in the Weddell Sea; its area, of 2,751 square miles (7,125 km^2), made it slightly bigger than Delaware (2,044 square miles; 5,294 km^2). One of the largest, seen in 1927, was more than 87 miles (140 km) long, but the largest of all known icebergs, measured by the icebreaker USS *Glacier* in 1956, was 207 miles (333 km) long and 62 miles (100 km) wide. Large sections of the LARSEN ICE SHELF have also broken free. Antarctic icebergs have not contacted the land surface and are white or blue in color.

Most icebergs have a specific gravity of 0.9, so about 90 percent of their volume lies below the sea surface.

ice core A sample of ICE for scientific study that is obtained by drilling vertically into a GLACIER and extracting a long cylinder. Glacial ice forms by the compression of snow, and each year's snowfall produces a recognizable band in the ice core. By counting the bands, starting from the top, it is possible to date the ice at each level.

Cores are taken from the polar ICE SHEETS, which are thick enough to yield records going back many thousands of years. Analysis of the ice then reveals much valuable information. Air trapped in small bubbles in the ice shows the composition of the atmosphere at a particular time—the content of CARBON DIOXIDE and METHANE, for example. DUST mixed with the ice indicates the relative amount of rainfall—the more dust there is the drier the climate was, because rain quickly washes dust from the air, reducing the amount reaching high latitudes—and dry conditions are associated with cold episodes. The oxygen isotope ratios (*see* OXYGEN) in the ice also reveal the temperature at the time the snow fell. *See* GREENLAND ICECORE PROJECT; GREENLAND ICE SHEET PROJECT; and VOSTOK STATION.

ice crystals When WATER freezes it forms solid crystals, the shape of which is determined by the shape of the water molecules from which they are made. A water molecule consists of two atoms of HYDROGEN (H + H) and one of OXYGEN (O) to give H_2O. These form an isosceles triangle with an apex angle, at the center of the oxygen atom, of 104.5° and one hydrogen atom at the tip of each leg of the triangle. The length of each leg is 1.00 Å. Molecules are linked to one another by hydrogen bonds (*see* CHEMICAL BONDS), each of which is 1.76 Å long. The linkage can be described as O—H … O, where the three dots represent the hydrogen bond.

As the temperature falls, the molecules move closer together. Each molecule bonds to four neighboring molecules. Its two hydrogen atoms bond to the oxygen atoms of two adjacent molecules, and its oxygen atom bonds above and below to one hydrogen atom of each of two adjacent molecules. This results in a hexagonal structure when seen from above and in crystals that consist of stacks of puckered hexagonal rings. These rings join together, side by side, to form puckered hexagonal layers at right angles to the axes of the hexagons.

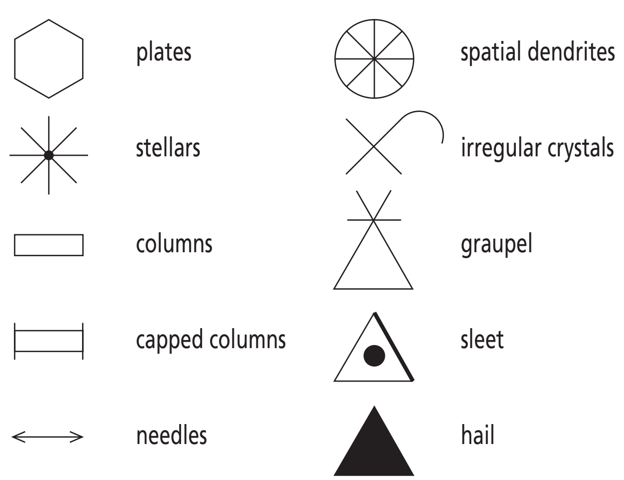
Each molecule is bonded to four others, but because of the shape of the molecule its hydrogen atoms can face toward any two of those four molecules. This allows each molecule to be oriented in one of six different ways. Each of the six orientations is equally probable, but whichever orientation occurs requires that the orientation of molecules nearby must be such as to maintain all the hydrogen bonds.

A consequence of this variability in orientation is that although all ice crystals are hexagonal, they occur in a variety of shapes. This affects the shapes of SNOWFLAKES, which are aggregations of ice crystals.

In 1951, an international system was adopted for classifying the shapes of ice crystals and the objects made from them. The classification recognizes ten types and there is a symbol for each to help with reporting them:

Plates are flat, hexagonal rings.
Stellars are rings with six points
Columns are cylinders that are hexagonal in cross section; columns are sometimes joined together.
Capped columns are columns that have a bar at each end. They may also be joined together and when they are the bars remain intact.
Needles are fine, resembling splinters, and they may be joined together.
Spatial dendrites are crystals with many fine branches, resembling fern fronds. These are what make the familiar frost patterns on windowpanes.
Irregular crystals are clumped together and have no regular shape. They are chaotic, as their name suggests.

In addition to these, there are three more categories for graupel, sleet, and HAIL.



The standard symbols that are used to designate the 10 recognized types of ice crystals

A sharp spike, hexagonal in cross section, which projects from an ice crystal is also called a dendrite. Crystals accumulate dendrites by diffusing (*see* DIFFUSION) through a cloud where the temperature is warmer than about 14°F (-10°C). Water droplets solidify by DEPOSITION, thereby becoming attached to the growing crystal. Where adjacent dendrites interlock, their crystals are held together, and once crystals have begun to aggregate in this way they will grow into snowflakes, which can become large. An approximately spherical ice crystal that has branches extending in all directions from a central nucleus is a type of dendrite called a spatial dendrite.

Acicular ice, also known as fibrous ice and satin ice, forms as long, pointed crystals and hollow tubes of varying shapes, with air held in the tubes and between the crystals. Acicular means "needle-shaped."

Ice prisms, also called diamond dust, are ice crystals so tiny they are barely visible. They seem to hang suspended in the air, twinkling as they catch and reflect the sunlight. They are shaped as needles, columns, or plates, and are seen only in extremely cold weather. They may fall from stratus, nimbostratus, or stratocumulus cloud (*see* CLOUD TYPES), but sometimes they occur when the sky is cloudless, forming a type of ice FOG.

Accretion is the process by which an ice crystal grows as it falls through a cloud containing many small, supercooled water droplets (*see* SUPERCOOLING). If the water droplets are very supercooled, so their temperature is well below freezing, they freeze immediately on contact with the ice crystal. New crystals are added one on top of another, with air trapped between them. This produces a loose, spongy structure typical of graupel (*see* HAIL). If the water droplets are only slightly supercooled, they may not freeze instantaneously. Instead, they form a layer of liquid water that surrounds the ice crystal before freezing as clear ice. As more droplets are added the ice crystal grows into a hailstone.

An ice splinter is a fragment of ice that becomes detached from an ice crystal as the crystal grows inside a cloud. Vertical air currents detach the splinters, which then act as fresh FREEZING NUCLEI. Splinters also form in cumulonimbus storm clouds, where there are very vigorous vertical currents and also supercooled water droplets. The splinters, released when supercooled droplets freeze, are so small that the air currents carry them to the top of the cloud, where they accumulate, because they weigh too little to fall. They carry a positive electric charge and their accumulation high in the cloud is a major factor in the separation of charges that eventually breaks down in sparks of LIGHTNING.

A fragmentation nucleus is a tiny splinter of ice that is snapped off from a larger ice crystal during a collision between crystals. The fragment then serves as an ice nucleus onto which a new ice crystal will grow.

Icelandic low One of the two semipermanent areas of low pressure in the Northern Hemisphere (the other is the ALEUTIAN LOW). The Icelandic low is centered between Iceland and Greenland, between about 60°N and 65°N. It is described as semipermanent because although it forms, dissipates, and reforms, it is present for most of the year and moves very little. It is farther north than the Aleutian low because of the warm water carried northwards by the Gulf Stream (*see* APPENDIX VI: OCEAN CURRENTS), and it covers a much larger area in winter, when the sea is warmer than the adjacent continents, than it does in summer.

The intensity of the low varies, pressure being lowest in winter, when the atmospheric circulation is strong. The average pressure at the center in January is 996 mb and in July 1008 mb. The Icelandic low generates many storms. These are carried eastward along the polar FRONT by the prevailing westerly winds of middle latitudes and account for the storminess of the North Atlantic, especially in winter. The Icelandic low is also involved in the NORTH ATLANTIC OSCILLATION, which is a periodic fluctuation in the distribution of pressure that has a major effect on weather in Europe.

ice sheet A layer of ICE that covers an extensive area of land and forms by the compression of snow that does not melt in summer. Snow that falls each year remains lying above the snow that fell in previous years and as the layers accumulate their combined weight compresses the lower layers, packing the ICE CRYSTALS together until they form solid ice. At the base of the ice sheet the weight causes ice to flow outward. Since flowing ice is known as a GLACIER, an ice sheet can also be called a glacier.

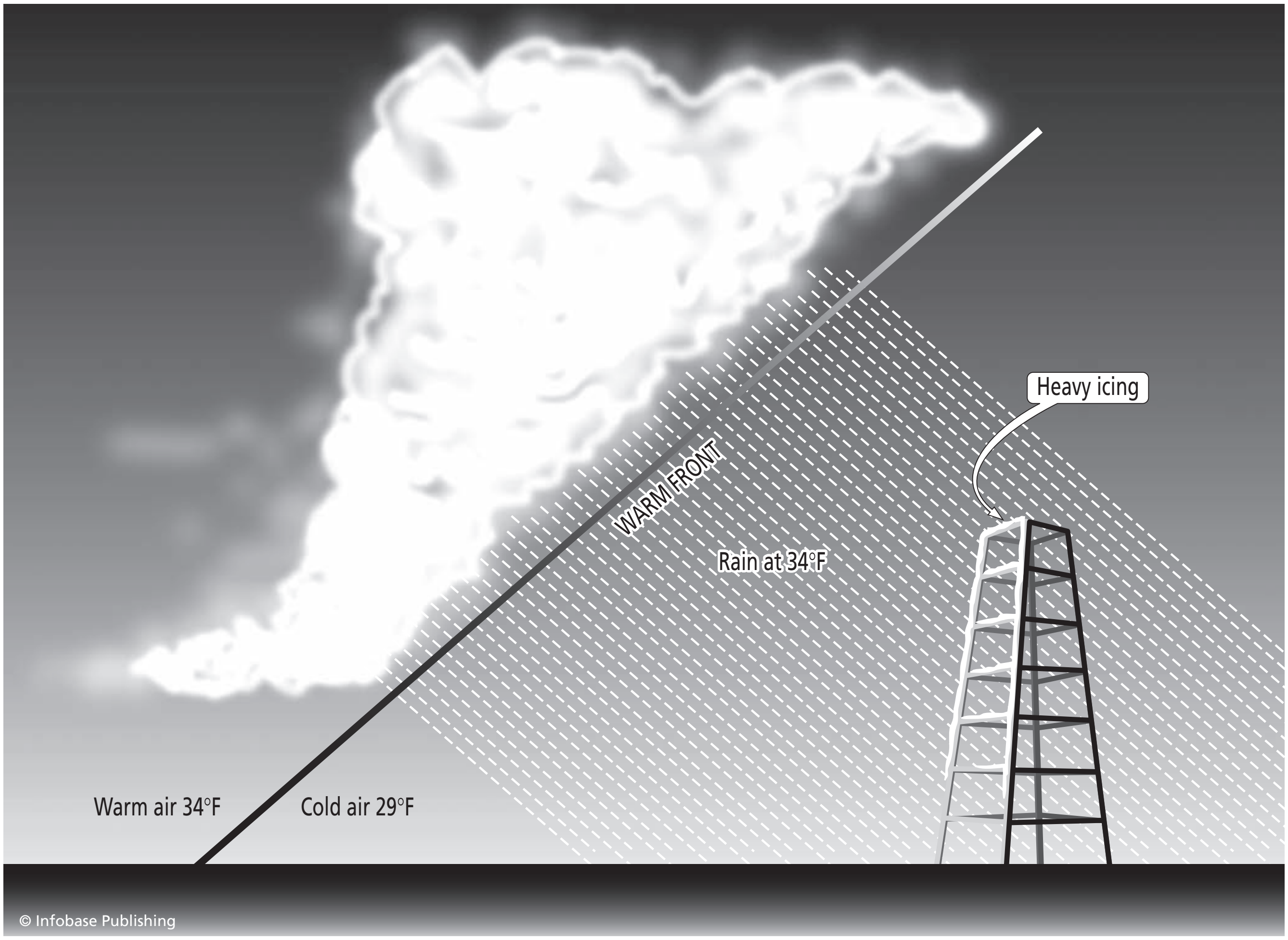
The GREENLAND ICE SHEET is the largest in the Northern Hemisphere, but the Antarctic ice sheet is very much bigger. It covers about 5.4 million square miles (13.9 million km^2) to an average depth of 6,900 feet (2,100 m) and contains more than 7 million cubic miles (29 million km^3) of ice. It has three parts. Ice on the Antarctic Peninsula comprises local ice caps, glaciers, and ICE SHELVES. The main part of Antarctica is divided in two by the Transantarctic Mountains. West Antarctica is largely covered by ice covering a land surface that in places is below sea level, as well as offshore islands. The West Antarctic Ice Sheet (WAIS) is less securely grounded than the East Antarctic Ice Sheet (EAIS). The WAIS flows toward the sea through a number of outlet glaciers. Beyond the coast it forms large ice shelves. The EAIS is much bigger than the WAIS, with an area of about 3.9 million square miles (10.2 million km^2). Its ice sheet is securely bonded to the underlying rock.

ice shelf A sheet of ice that extends from an ICE SHEET and covers an area of sea. Ice sheets flow outward through outlet GLACIERS under the pressure exerted by the weight of ice at the center of the sheet. Where they reach the coast the sheets continue to advance into the shallow water, still in contact with the solid surface of the seabed. As they enter deeper water, the ice loses contact with a solid surface and floats. The vertical movement of the water beneath the ice, due to tides, then causes sections to break free, as ICEBERGS.

An ice shelf forms where an ice sheet crosses a coast and enters a wide, but partly enclosed bay. It remains secured to land at either side, but there is water beneath its center. There are a few small ice shelves in the Arctic, but there the GREENLAND ICE SHEET, which is the only arctic ice sheet, is contained by mountain ranges.

The really big ice shelves are found off the coast of Antarctica. The Ronne–Filchner, which has a large island near its center and for that reason is sometimes considered to be two distinct ice shelves, covers part of the southern Weddell Sea, and the Ross Ice Shelf covers part of the southern Ross Sea. Each has an area of more than 154,400 square miles (400,000 km^2). In recent years substantial parts of the LARSEN ICE SHELF have broken free, raising fears for the long-term stability of the West Antarctic Ice Sheet.

ice storm A storm of freezing rain (*see* PRECIPITATION) that deposits thick layers of ICE onto structures such as radio masts, the rigging of ships, trees, and telephone wires. It is sometimes called silver thaw (*see* LOCAL CLIMATES), because it is often followed by warmer conditions. The ice is also known as black ice, because it is transparent and therefore almost invisible as a coating on roads and sidewalks.



Ice forms on the mast because rain, at a temperature just above freezing, cools as it falls through air that is below freezing temperature and freezes on contact with the chilled surface of the mast.

Ice storms usually occur just ahead of a warm front, where the temperature of the air in the lower few hundred feet of the cold sector ahead of the front is well below freezing and surfaces in the cold air are at the same temperature. In the warm air behind the front, the temperature must be a degree or two above freezing, and water droplets in the frontal cloud must also be slightly above freezing temperature. Finally, there must be a strong wind to drive the rain so it falls at an angle to the vertical. These conditions are crucial. A difference of just a few degrees determines whether the precipitation is in the form of SNOW, cold rain, or whether it causes an ice storm.

Suppose the warm air and the water droplets falling from it are at 34°F (4°C) and the cold air and surfaces below the front are at 29°F (-5°C). Rain falling from the cloud enters colder air. The droplets cool as they fall until, by the time they strike a surface, they are at or just below freezing. The temperature of the surface is also below freezing.

Even then, the ice storm will soon abate unless the supply of cold air is constantly replenished. This is because the freezing of water droplets releases LATENT HEAT, which warms the surrounding air.

As a droplet strikes a surface, the water that first makes contact with the surface freezes instantly. The remainder of the droplet flows over the newly formed ice, spreading to the sides, and it also freezes as it encounters the cold surface. As more droplets fall, the layer of ice grows steadily thicker and, because a strong wind is driving the rain, the ice layer thickens on the sides of objects that are facing into the wind much more rapidly than it does on the other, more sheltered sides. It is not only solid objects like radio masts and trees that accumulate ice. People walking into the wind will also be coated, although their movement and the flexibility of their clothes breaks the ice into fragments before the ice layer can become very thick.

In a severe ice storm the ice can form a very thick layer and it can be extremely disruptive. It is dangerous for aircraft to land and take off when runways are thickly covered with ice, so air traffic is subject to delays. Railroads can also be immobilized when the rails are coated with ice, and road accidents increase when conditions are icy.

Ice is heavy and this causes other hazards. In January 1940, an ice storm in southern England snapped telephone wires that later were found to be loaded with up to 1,000 pounds (450 kg) of ice. Telephone poles snapped when their load of ice exceeded about 11 tons (10 tonnes). Ice can form layers several inches thick on radio masts and the superstructure of ships. That imposes enough weight to cause structural damage and workers must struggle to remove the ice before it can do serious harm.

Winter snow and ice deposited by an ice storm on trees in the United States. ***(Rob & Ann Simpson/Visuals Unlimited)***

Roosting birds have frozen to tree branches during an ice storm, and then died from starvation because they were unable to free themselves. Ground-dwelling birds have had their wings coated with ice, which kept them grounded, although perhaps they were safe from predators, because it has been known for cats caught in severe ice storms to be frozen to the ground by their paws.

Ice storms can now be predicted. The risk can be estimated from the temperatures and dew point temperatures (*see* DEW) in the air at the height where the pressure is 850 mb—about 5,000 feet (1,500 m)—and the THICKNESS of the layers between 850 mb and 1,000 mb and between 500 mb and 1,000 mb. The mean temperature of the air in these layers can be calculated from the thickness of the layers. In the United States, the NATIONAL WEATHER SERVICE issues warnings of impending ice storms.

Indian Ocean Experiment (**INDOEX**) An international meteorological field experiment using data transmitted from METEOSAT-5 that studies AIR POLLUTION, CLOUDS, interactions between clouds, and solar radiation in the INTERTROPICAL CONVERGENCE ZONE over the Indian Ocean. The experiment is supported by agencies and institutes in France, Germany, India, the Netherlands, Sweden, the United Kingdom, and the United States.

Further Reading

Scripps Institution of Oceanography. "Indian Ocean Experiment: An International Field Experiment in the Indian Ocean." La Jolla, California: Scripps Institution of Oceanography, University of California, San Diego. Available online. URL: http://www-indoex.ucsd.edu/. Posted August 29, 1999.

inductance A property that is possessed by electric circuits. It takes two forms: self-inductance and mutual inductance. Self-inductance is the production of an electromotive force when the current flowing through the circuit changes. Mutual inductance is the production of an electromotive force when the current flowing through a neighboring circuit changes. The SI unit of inductance is the henry.

industrial melanism An evolutionary adaptation to industrial AIR POLLUTION in which a species of animal adjusts its body color to that of its surroundings when these have been discolored by soot. More than 100 species of European and North American moths and butterflies have responded in this way; the most famous is the peppered moth (*Biston betularia*), which was described in 1973 by the British ecologist H. B. D. Kettlewell, who studied the phenomenon in England.

Variations in shape, size, or color are found among individuals of many species. The phenomenon is known as polymorphism, which means many (*poly-*) forms (*morphs*). The peppered moth, an insect about 2 inches (5 cm) across when its wings are extended, is ordinarily ivory-colored with dark speckles and blotches. It rests on tree bark and fences that are covered in lichens, against which its coloration makes it almost invisible. There is also a dark form of the moth, known as the melanic form because melanin is the pigment that gives animals a dark color. In melanic peppered moths the dark spots cover much more of the wings, and the most extreme form, called the *carbonaria* subspecies (*B. betularia carbonaria*), is almost completely black. A single gene that is dominant to the pale gene causes this color pattern.

The first *carbonaria* specimen was recorded in 1848, near Manchester, England. Smoke and sulfur dioxide from factories had killed most of the lichens and blackened tree bark and fences with soot. The ordinary, pale moth stood out strongly against this background, but the melanic form was well camouflaged. It was then found that the melanic form was much more common than the pale form in heavily polluted industrial areas and the pale form was more common in unpolluted rural areas.

Kettlewell bred several thousand moths and liberated both pale and melanic forms, some in the industrial Midlands and Northwest of England and others in the rural south. Then he watched with binoculars to see what happened. In polluted areas, where the background was dark, melanic forms were better hidden from birds and more of them survived. In unpolluted areas the pale forms survived better.

Melanic forms had become more common than the pale forms in polluted parts of the country, but after pollution controls including smoke abatement legislation were introduced the situation started to change. Gradually the lichens returned, soot deposition declined, and the proportion of pale moths increased. Prior to 1962, when controls were imposed, there was a 41–55 percent chance of a pale moth's being caught. After 1963 this fell to 21–22 percent.

The change from the pale to the melanic form in response to industrial pollution, industrial melanism, is a clear example of natural selection in action.

inertial reference frame A location that is not accelerating (*see* ACCELERATION) and from which the acceleration of other bodies can be observed accurately. The second of Newton's LAWS OF MOTION states that the rate at which a body accelerates is proportional to the force exerted upon it. Newton assumed, however, that the acceleration is measured from a platform that is not itself accelerating, that is, from an inertial reference frame. Unless such a frame is used, measurements of acceleration will be inaccurate, the second law may appear to be flouted, and mysterious countervailing forces may manifest themselves.

The pilot of a fast jet airplane is pushed hard into the seat when the aircraft pulls out of a dive. If it were possible to measure his weight at that moment, it would be found to be greater than his weight measured on the ground before takeoff, because it is measured while his body is accelerating rather than while he is at rest and in an inertial reference frame. A passenger riding in a car that takes a corner at speed feels pushed outward. This is the supposed "centrifugal force" (*see* CENTRIPETAL ACCELERATION). It is unreal, but it appears to be real because the passenger is attached to the car, which is accelerating, and is therefore in the same reference frame. An observer in an inertial reference frame, outside the car, could see that the car tended to continue moving in a straight line (the first law of motion) but that a force drawing it toward the center of the turn (the centripetal force) caused it to follow a curved path. Both the passenger and the fighter pilot are being pulled inward toward the center of the circle their motion is describing, not pushed outward, and there is no centrifugal force.

All meteorological observations are made from a reference frame that is fixed to the Earth, which is accelerating because of its rotation. That is why moving air appears to be deflected by the CORIOLIS EFFECT, which is sometimes incorrectly called a "force." In order to understand the way air moves, the actual reference frame used to observe it must always be converted into an inertial reference frame.

Initial Joint Polar-Orbiting Operational Satellite System (IJPS) A system of meteorological satellites in polar ORBITS that were established and are operated jointly between the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION and EUMETSAT. The system comprises two satellite systems in polar orbits, together with the ground segments they cover. IJPS came into operation in 2003 and enhances and supplements climate monitoring and NUMERICAL FORECASTING.

Further Reading

NOAA. "Initial Joint Polar-Orbiting Operational Satellite System." Office of Systems Development, NOAA Satellite and Information Service. Available online. URL: http://projects.osd.noaa.gov/IJPS/. Accessed December 21, 2005.

insolation The amount of solar radiation that reaches the surface over a unit area of the surface of the Earth. The word insolation is a contraction of *in*coming *sol*ar radi*ation*. This varies with the SEASONS and according to weather conditions.

Knowing the insolation at a particular place is useful for agricultural and horticultural planning, and the insolation is also botanically important. Insolation is calculated for a whole day, then averaged over a number of days, chosen to include both cloudy and sunny conditions. Insolation is measured in megajoules per square meter (MJ/m^2). Sunshine is most intense at noon, and the average total insolation during the hours of daylight is equal to $2/\pi$ multiplied by the noon maximum. A typical value for insolation in middle latitudes is about 25 MJ/m^2.

interception The process by which an exposed plant surface catches PRECIPITATION, or the proportion of the total precipitation that falls on particular surfaces, such as the leaves of a tree. Sunshine is also subject to interception by tall objects that cast shadows such as hills and buildings and by gases or particles present in the air.

interference The effect of imposing one set of waves upon another. This produces a new wave with a different form and characteristics (*see* WAVE CHARACTERISTICS) from either of the waves from which it is made. If the two interfering sets of waves are in phase, so their wave crests and troughs are aligned, the amplitude of the resultant wave will be the sum of the amplitudes of the two waves. This is called constructive interference. If the waves are directly out of phase, so the crests of one are aligned with the troughs of the other, the amplitude of the resultant wave will be equal to the difference between the two amplitudes. This is called destructive interference, and if the two waves are of similar amplitude, they will cancel each other. When light is diffracted (*see* DIFFRACTION) some colors (wavelengths) will become out of phase. These will be subtracted from the light, causing the light to become colored by the wavelengths that are in phase.

interferometer An instrument that is used to measure the wavelength of radiation (*see* WAVE CHARACTERISTICS and SOLAR SPECTRUM). It works by measuring the fringes that form between wavelengths that interfere with each other.

An etalon is an interferometer that comprises half-silvered plane-parallel glass or quartz plates a fixed distance apart with a film of air enclosed between them.

interglacial A prolonged period of warmer climates that separates two GLACIAL PERIODS. As an interglacial progresses in mid-latitudes, POLLEN analysis reveals that tundra vegetation is replaced by a variety of herbaceous plants, which are replaced in their turn, first by coniferous and then by broad-leaved, deciduous forest. In higher latitudes the progression may proceed no further than the establishment of coniferous forest and in continental interiors, where the climate is too dry for forest, grassland may become the predominant vegetation type. The progression toward more warmth-loving species is reversed as an interglacial nears its end and the climate enters a new glacial period. An interglacial typically lasts for about 10,000 years. At present we are living in an interglacial known as the Flandrian.

Interglacials that occurred during the PLEISTOCENE are described below, commencing with the earliest.

Antian was an interglacial that occurred in Great Britain about 1.8 million years ago. It is equivalent to the Tiglian interglacial of continental Europe. The Antian (Tiglian) occurred at the very start of the Pleistocene epoch (some authorities place it in the late Pliocene) and it is believed to have been a time when average temperatures were falling.

Bramertonian, known as the Waalian in northwestern Europe, was an interglacial period in Great Britain that began about 1 million years ago and ended about 900,000 years ago. It followed the Baventian glacial and preceded the Pre-Pastonian glacial. It has no known North American equivalent.

Pastonian was an interglacial that occurred in Great Britain from 800,000 years ago until 740,000 years ago.

Aftonian was an interglacial that occurred in North America after the end of the Nebraskan Glacial, and that was followed by the Kansan Glacial. The Aftonian began about 600,000 years ago and ended about 480,000 years ago. It is approximately equivalent to the Cromerian interglacial of Great Britain (preceding the Anglian glacial), the Cromerian complex of northwestern Europe, and the Donau-Günz interglacial of the European Alps. Dating is uncertain, but the Cromerian lasted from approximately 750,000 years ago until about 350,000 years ago. During the Aftonian summers were milder and winters warmer than they are in North America today.

Yarmouthian was an interglacial period in North America that followed the Kansan glacial and preceded the Illinoian glacial. It began about 230,000 years ago and ended about 170,000 years ago. The Yarmouthian is approximately equivalent to the Hoxnian of Great Britain, the Holsteinian of northwestern Europe, and the Mindel-Riss of the European Alps. At various times during the Yarmouthian average temperatures were both lower and higher than those of today.

In Great Britain, the Hoxnian followed the Anglian glacial and preceded the Wolstonian glacial. It is named after the village of Hoxne, Suffolk. Dating is uncertain, but the Hoxnian probably began about 250,000 years ago and ended about 200,000 years ago. Early humans (*Homo erectus*) were making stone hand-axes in Britain at this time. The climate during the Hoxnian was strongly oceanic (*see* OCEANICITY), with high rainfall, mild winters, and warm but not hot summers.

The Mindel-Riss lasted from about 250,000 years ago to about 200,000 years ago. It was formerly known as the Great Interglacial, but this name is no longer used.

Sangamonian was the interglacial that followed the Illinoian glacial and preceded the most recent (Wisconsinian) glacial in North America. The Sangamonian began about 120,000 years ago and ended about 75,000 years ago. It is approximately equivalent to the Ipswichian of Great Britain, the Eemian of northwestern Europe, and the Riss-Würm of the European Alps.

The Ipswichian followed the Wolstonian glacial and preceded the Devensian glacial. It lasted from about 130,000 years ago until about 72,000 years ago and is named for glacial deposits found near the town of Ipswich, Suffolk. Deposits dated from the very early Ipswichian and taken from the River Thames in London have given this interglacial the alternative name of Trafalgar Square interglacial. Those deposits include remains of plants that are no longer found so far north as Britain, and of hippopotamus, elephant (*Elephas antiquus*), and rhinoceros. This suggests that average summer temperatures during the Ipswichian were 3.6°F–5.4°F (2°C–3°C) warmer than those of today.

The Eemian interglacial in northern Europe lasted from about 130,000 years ago until about 72,000 years ago. It followed the Saalian Glacial and preceded the Weichselian Glacial. Sea levels rose during the Eemian, forming a large inland sea, called the Eem Sea, in what are now the Netherlands and northern Germany.

The Riss-Würm interglacial occurred in the European Alps from about 130,000 years ago until 70,000 years ago. It was the last interglacial before the onset of the Würm Glacial, which is equivalent to the Devensian Glacial in Britain and the Wisconsinian Glacial in North America.

The Flandrian is the present interglacial, also known as the Holocene interglacial in North America and Great Britain, although that is also the name of the present epoch of geologic time (*see* APPENDIX V: GEOLOGIC TIMESCALE). The Flandrian began when the most recent glacial period came to an end, approximately 10,000 years ago. The warmest part of the Flandrian, known in Europe as the Atlantic period and in North America as the Hypsithermal, lasted from about 7,500 to 5,000 years ago. The climate then was warmer than the climate of the present day. Soon after the postglacial warming began, it was interrupted by a return to near ice-age conditions (*see* YOUNGER DRYAS). The Flandrian has already lasted for about the average duration of an interglacial, and scientists agree that eventually it will give way to a new glacial period. There is no agreement, however, about when the present interglacial will end, or how abruptly, nor about how far the ICE SHEETS are likely to extend during the next glacial period.

Intergovernmental Panel on Climate Change (IPCC) An organization that was established in 1988 by the WORLD METEOROLOGICAL ORGANIZATION (WMO) and the United Nations Environment Programme (UNEP). It is open to all member nations of WMO and UNEP, and its task is to assess the scientific, technical, and socioeconomic information that is relevant to changes in climate that are caused by human activity and their consequences.

The IPCC has three Working Groups. Working Group I assesses the science. Working Group II considers the effects of climate change on socioeconomic and natural systems and the extent to which they may adapt. Working Group III assesses the options for mitigating climate change, in particular by reducing the emission of greenhouse gases (*see* GREENHOUSE EFFECT). The IPCC meets in plenary session approximately once each year to discuss and accept the reports from its Working Groups.

The scientific working group (Working Group 1) divides its task into 18 subject areas, each with a lead author. The 18 lead authors are responsible for gathering contributions on their specified topics and for writing that section of the overall report. Hundreds, possibly thousands of scientists contribute to the report of Working Group 1.

Further Reading

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson. *Climate Change 2001: The Scientific Basis.* Cambridge: Cambridge University Press and the Intergovernmental Panel on Climate Change, 2001.

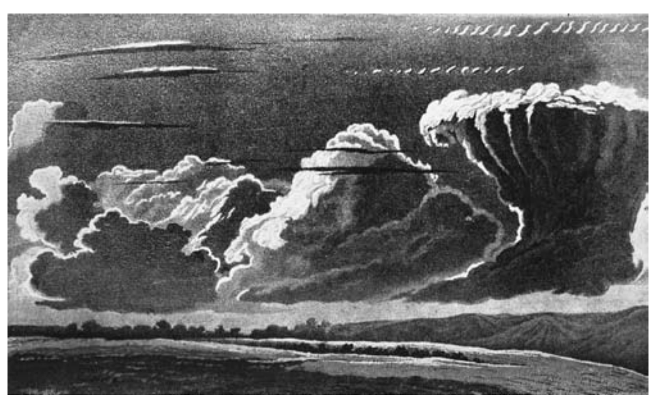
International Cloud Atlas A book, published by the WORLD METEOROLOGICAL ORGANIZATION, which contains the pictures and definitions against which clouds are classified (*see* CLOUD CLASSIFICATION). The complete *Atlas* is in two volumes and there is also a single-volume, abridged version.

Volume I of the complete *Atlas* is a loose-leaf manual describing the way clouds and other atmospheric phenomena should be observed. Volume II contains 196 pages of photographs, 161 of them in color, together with concise yet detailed captions defining CLOUD TYPES. The abridged version contains 72 photographs, some in color and some in black-and-white, of all the cloud types and a variety of other phenomena, such as FOG and WATERSPOUTS, together with a text describing cloud observation.

The first edition of the *Atlas* was published in Paris in 1896 "by order of the International Meteorological Committee." The plan to produce a standard classification of clouds was agreed at the World Meteorological Congress held in 1874. The project drew on observations made by meteorologists in many countries, and the *Atlas* was compiled by the Cloud Commission established by the Committee. The observations contributed by American scientists were made at the Blue Hill Observatory, to the south of Boston, Massachusetts. The classification that was used was based on the system devised by Luke Howard (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) and published in 1803. The *Atlas* divides clouds into 10 major types, called genera. These are subdivided into 14 species and nine varieties. There are also accessory cloud features, such as pileus, tuba, and velum.

The *International Cloud Atlas* has been revised several times since it was first published. The most recent edition of Volume I was published in 1956 and revised in 1975, the latest edition of Volume II was published in 1987, and the latest edition of the abridged version was published in 1956. The text is available in English, French, and Spanish editions.

(The latest edition of the *Atlas* can be ordered from the World Meteorological Organization Web site



An illustration from an early cloud atlas, *Wolken und andere Erscheinungen* by Thomas Forster, published in 1819. *(Historic NWS Collection)*

at www.wmo.ch/web/catalogue/New%20HTML/frame/engfil/407.html.)

International Geosphere–Biosphere Program (IGBP) A project that was launched in 1986 by the International Council of Scientific Unions, which is the body that coordinates the activities of national scientific societies and academies. The aim of the IGBP is to "describe and understand the interactive physical, chemical and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring, and the manner in which changes are influenced by human actions." In order to achieve this aim, the IGBP seeks to establish a scientific basis from which to detect and measure changes, including climate change. This task is divided into six components: atmospheric chemistry; terrestrial ecosystems; biological drivers of the water cycle; coastal land–ocean interactions; ocean circulation; and past global changes. Scientists of more than 100 nations are engaged in studying these areas.

The IGBP has also established a network of regional centers where the local environment is studied, scientists are trained, and the regional relevance of change is estimated. This program is the Global Change SysTem for Analysis, Research and Training (START). START has also established 14 regional research networks in less-industrialized countries.

Further Reading

IGBP. "International Geosphere–Biosphere Program." Available online. URL: www.igbp.kva.se/cgi-bin/php/frameset.php. Accessed December 22, 2005.

International Phenological Gardens (IPG) A network of gardens in Europe that covers an area from Macedonia (42°N) to Scandinavia (69°N) and from Ireland (10°W) to Finland (27°E). All the gardens grow genetically identical clones of trees and shrubs. Records are kept of the dates of phenological events, such as the unfolding of leaves, growth of shoots, flowering, leaf coloring, and leaf fall.

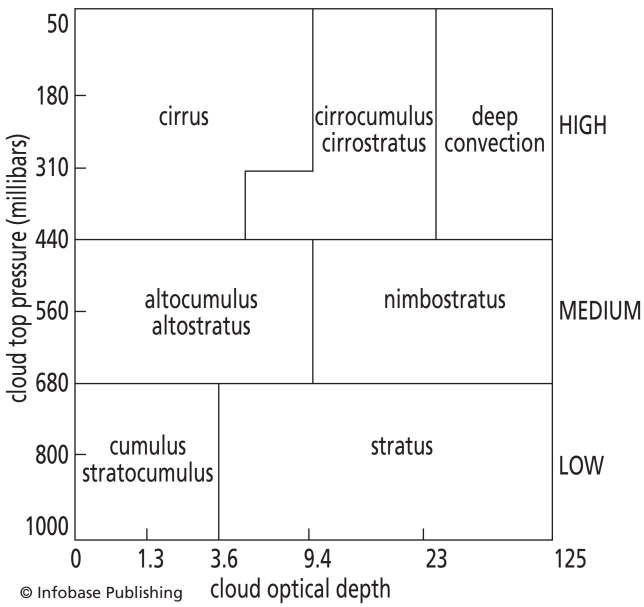
International Polar Year The year from August 1882 until August 1883, during which scientists conducted the first international collaboration to investigate the environment of the Arctic, and especially arctic meteorology, auroras (*see* OPTICAL PHENOMENA), and the Earth's magnetic field. The participating nations financed the establishment of 12 observing stations in high latitudes, six of which were sited on the barren surfaces of the islands to the north of Eurasia and North America. Several of these stations remained occupied through the winter, and almost all of them recorded meteorological observations. The longest continuous weather records collected from this region during the 19th century covered a period of 1,000 days, from 1895 to 1897, and were made at Cape Flora, Franz Josef Land.

Although the International Polar Year focused attention on the Arctic, the observing stations were not maintained once the year had ended, and the record of meteorological data from the Arctic is much sparser than that from Antarctica, which has been studied more thoroughly. A few permanent stations were established around the edges of the Arctic in about 1915, but there has never been one at the North Pole.

A Second International Polar Year was held from 1932 to 1933. Many more stations were established during that year around the continental coasts and on islands. The Soviet Union opened a series of them. Many of the stations opened during the second year have produced a constant meteorological record over many years. A few years later, in 1937, the Soviet Union deployed the first meteorological station on the surface of floating ice. It began about 30 miles (50 km) from the North Pole and survived for 18 months, drifting south with the East Greenland Current (*see* APPENDIX VI: OCEAN CURRENTS). The United States began using similar floating observation stations in 1946. Many more observing stations were established during the International Geophysical Year, from 1957 to 1958.

International Satellite Cloud Climatology Project (ISCCP) A program that was established in 1982. It was the first project of the World Climate Research Program, which is part of the WORLD CLIMATE PROGRAM. It began collecting data on July 1, 1983.

The ISCCP gathers a wide range of satellite radiation measurements at wavelengths covering the whole of the visible and infrared spectra, with spatial resolutions from 33 feet (10 m) to 1,240 miles (2,000 km) and at time intervals of 1/2 hour to 30 days. The images are transmitted by satellites, some in polar ORBITS and others in geostationary orbits. The data are analyzed to obtain information about the location, extent, and types of cloud over the entire surface of the Earth. The ISCCP



The system of cloud classification that is used in the International Satellite Cloud Climatology Project is based on the atmospheric pressure at the cloud tops and the optical depth of the clouds.

has its own system for cloud classification, based on the atmospheric pressure at the tops of the clouds, measured in millibars, and their optical depth (*see* OPTICAL AIR MASS), which is a ratio and has no units.

International Satellite Land Surface Climatology Project (ISLSCP) A project in which satellite images are used to map vegetation. Data from the NORMALIZED DIFFERENCE VEGETATION INDEX is used to build illustrations based on a 1° latitude by 1° longitude grid that are then stored on CD-ROM and released to scientists as sets of CD-ROMs.

interstade (interstadial) A time of warmer weather that occurs during a GLACIAL PERIOD. An interstade lasts for about 1,000–2,000 years. It is of much shorter duration than an INTERGLACIAL and it may also be cooler, although this is uncertain. The vegetation present during an interstade, identified by POLLEN analysis, is typical of a climate cooler than that of an interglacial, but this may be because an interstade does not continue long enough for warmth-loving species to colonize the area.

The interstades described below are listed in date order, commencing with the earliest.

The Odintsovo interstade occurred in northern Europe during the Saalian glacial, which lasted from 170,000–120,000 years ago. It was a time when plants typical of temperate, broad-leaved forest grew. Odintsovo, where the evidence for it was first identified, is a town lying to the west of Murmansk, in northern Russia and close to the Finnish border.

The Odderade interstade occurred in northern Europe during the Weichselian glacial. The evidence for it was first identified at Odderade, in Schleswig-Holstein, Germany. The interstade lasted from 70,000–60,000 years ago. Tundra vegetation, perhaps with a few cold-tolerant trees, grew throughout northern Europe during the interstade. When the interstade ended, ice-age conditions returned.

The Chelford interstade occurred in Britain about 60,000 years ago, during the Devensian Glacial. Evidence for it has been found at Chelford, Cheshire, in northwestern England. At that time a coniferous forest similar to that now found in Finland covered the region. Conditions were similar to those during the Brørup interstade.

The Brørup interstade occurred about 59,000 years ago, during the Weichselian Glacial. Evidence for it comes from sediments that existed then in a lake beneath what is now a bog at Brørup, in West Jutland, Denmark. This lake lay beyond the limit of the ICE SHEET. During the interstade a forest consisting of coniferous trees with birch (*Betula* species) covered the area. The vegetation was similar to that found in England at about the same time during the Chelford interstade.

The Upton Warren interstade occurred in Great Britain during the Devensian glacial period, lasting from about 43,000 years ago until 42,000 years ago. Pollen analysis indicates that the British climate was similar to that of southern Sweden today. There were few trees and even pine (*Pinus* species) and birch (*Betula* species) trees were scarce. There could certainly have been no woodlands. The remains of insects suggest summer temperatures reached at least 59°F (15°C). This is warm enough for trees, and their absence is believed to be due to the short duration of the interstade, which did not allow sufficient time for them to spread northward and become established. These conditions probably extended over much of Europe. They were first identified at Upton Warren, a place in Worcestershire, England.

The Hengelo interstade, also called the Hoboken interstade occurred in northern Europe around 40,000 years ago, during the middle of the Devensian Glacial. July temperatures averaged about 50°F (10°C). Together, the Moershoofd (when summer temperatures were 43–45°F, 6–7°C), Denekamp, and Hengelo Interstades are equivalent to the Upton Warren Interstade.

The Denekamp interstade, also called the Zelzate interstade occurred in the Netherlands about 30,000 years ago. During the Denekamp, the average July temperature was about 50°F (10°C).

Bølling is a place in Jutland, Denmark, where there are sediments that were deposited on the bottom of a lake that existed toward the end of the Devensian glacial period. Remains found in the sediments indicate there was a period of warmer conditions that lasted from about 13,000 years ago until about 12,200 years ago. Temperatures then were as high as those of today, or even higher, but fell toward the end of the interstade. The Bølling Interstade was followed by the OLDER DRYAS STADE.

The Windermere interstade occurred in Britain from about 13,000 years ago until 11,000 years ago, during the latter part of the Devensian glacial period. The Windermere Interstade coincided with the Bølling, Older Dryas, and Allerød periods in Scandinavia.

Allerød is a place to the north of Copenhagen, Denmark, where clay is removed for making tiles and plant remains found at the site provide evidence of a period of warm, moist weather as the Devensian glacial period was drawing to a close. The lowest layer of clay contains evidence of the cold, Older Dryas Stade. Above this layer there is evidence of the warm Allerød interstade. The interstade began about 11,800 years ago and lasted for about 800 years before temperatures fell once more with the start of the YOUNGER DRYAS. During the Allerød the tundra vegetation disappeared, the soil stabilized, and birch (*Betula* species) woodland covered the area, together with other warmth-loving plants such as meadowsweet (*Filipendula ulmaria*). The Allerød was followed by the Younger Dryas stade.

(*See* APPENDIX VII: PLIOCENE, PLEISTOCENE, AND HOLOCENE GLACIALS AND INTERGLACIALS.)

Intertropical Convergence Zone (ITCZ) A belt surrounding the Earth and close to the equator, where the trade winds (*see* WIND SYSTEMS) of the Northern and Southern Hemispheres meet. Convergence (*see* STREAMLINES) of air from the northeast and southeast causes the air to rise. When the rising air reaches the tropopause (*see* ATMOSPHERIC STRUCTURE), at 39,000–49,000 feet (12–15 km), it moves away from the equator and descends again in the subtropics to rejoin the trade winds. This is the Hadley cell circulation (*see* GENERAL CIRCULATION). Convergence also produces low atmospheric pressure at the surface, and the ITCZ is a region of permanently low surface pressure, known as the equatorial TROUGH.

The ITCZ was formerly known as the intertropical FRONT. A front exists only where there is a marked contrast between two AIR MASSES. Such contrasts occur in some places within the ITCZ, but while the ITCZ remains close to the equator the characteristics of the air masses in the Northern and Southern Hemispheres are similar and there is no clearly marked front separating them. A front develops as the ITCZ moves away from the equator into the summer hemisphere, and it is most marked around the time of the summer SOLSTICE. In June and July, during the summer MONSOON, an intertropical front does exist over southern Asia and West Africa. Despite the name, however, even where it does exist, the intertropical front produces little distinctive weather and is quite unlike the frontal systems of middle latitudes.

The equatorial trough is a wide belt of low surface pressure that encircles the Earth. Winds in the trough are generally light and easterly, but this is also the location of the doldrums (*see* WEATHER TERMS). Rising air causes water vapor to condense, and the trough is the region where most equatorial PRECIPITATION occurs, although the amount of cloud is very variable and there are large areas of clear skies.

A wave disturbance called an equatorial wave sometimes develops in the equatorial trough over the Pacific Ocean when the trough is far enough from the equator for the CORIOLIS EFFECT to generate cyclonic motion (*see* CYCLONE). Equatorial waves are more common in the Northern Hemisphere than the Southern Hemisphere, and they seldom generate winds that intensify into TROPICAL CYCLONES.

Oceans cover most of the equatorial belt. Consequently, the trade winds gather moisture and the air rising in the ITCZ is moist. Its WATER VAPOR condenses, producing towering clouds and heavy precipitation. In satellite photographs, a line of cloud in the equatorial belt marks the position of the ITCZ. The cloud is not continuous, but occurs in masses of cloud about 60 miles (100 km) across. These often appear as a series of waves, 1,200–2,500 miles (2,000–4,000 km) apart, which move slowly from east to west. They are known as easterly waves and are implicated in the development of tropical storms (*see* CYCLONE) and TROPICAL CYCLONES.

Over the ocean, but not over the continental land masses, the ITCZ also marks the region of highest temperature. This does not coincide with the geographic equator (*see* THERMAL EQUATOR). The difference arises because the location of the ITCZ depends strongly on the HUMIDITY of the air. Air has sufficient BUOYANCY to rise all the way to the tropopause only if it gains energy from the release of LATENT HEAT through the CONDENSATION of its water vapor. Air over land is less buoyant and although low-latitude deserts, such as the Sahara and Australian Deserts, are much hotter than the ocean, the ITCZ lies on the side of them closest to the equator.

The position of the ITCZ changes with the SEASONS. After each EQUINOX, as the line joining places where the noonday Sun is directly overhead moves away from the equator, the ITCZ follows it. The largest seasonal migration occurs over land. Over South America and Africa, in January the ITCZ lies at about 15°S. In July it lies at about 15°N over Africa and at about 25°N over Asia. There is much less movement over the oceans. In January, the ITCZ is close to the equator over all the oceans, and in July it lies at about 5–10°N over the oceans. During the Northern Hemisphere summer, increased warmth causes an increase in EVAPORATION and cloud formation in the ITCZ. In winter, cooler temperatures bring a reduction in the amount of cloud. It is because the ITCZ never crosses the equator over the eastern and central Atlantic that hurricanes very seldom occur in the South Atlantic (in fact, only one such storm, Catarina 2005, has ever been recorded).

In addition to its seasonal migrations, the position of the ITCZ also varies from year to year, following changes in sea-surface temperatures. If the sea is warmer than average, the ITCZ will be displaced toward the warm area. This happens during ENSO events.

inverse square law A law stating that the magnitude of a physical quantity is inversely proportional to the square of the distance between the source of that quantity and the place where it is experienced. The inverse square law determines the proportion of the total amount of energy emitted by the Sun that reaches each body in the solar system.

Imagine that the Sun is surrounded by a series of concentric spheres, each sphere having a radius equal to the distance between a planet and the Sun. Mercury "sits on" the innermost sphere, Venus on the next one, then Earth, Mars, and so forth. The whole of the energy emitted by the Sun reaches each of the spheres in turn. There is no diminution in the amount of energy as it travels. At each sphere, the solar energy is distributed evenly over the surface area of the sphere, which is equal to $4\pi r^2$, where r is the radius of the sphere. Since the area of the sphere is proportional to the square of its radius—the distance between the surface (or planet) and the Sun—the amount of energy arriving at any part of the surface, such as a planet, must be inversely proportional to the square of the radius ($1/r^2$). Consequently, the amount of solar radiation reaching each planet decreases rapidly with increasing distance from the Sun.

inversion The condition in which the air temperature increases with height, rather than decreasing. The layer of air in which the temperature increases with height is called an inversion layer. A temperature inversion that begins at ground level, so that in the lowest layer of air the temperature increases with height, is called a surface inversion or ground inversion.

Inversions often occur near the surface and are especially common in some areas that are surrounded by mountains. The shelter of the mountains restricts the movement and mixing of air, creating conditions in which an inversion can develop. Inversions over the ocean are also common in the TROPICS.

There are several ways in which an inversion can develop. On clear nights the ground cools by radiating the warmth it accumulated during the day. This can produce a low-level radiation inversion. The dry air is almost transparent to outgoing infrared radiation (*see* SOLAR SPECTRUM), so the cooling is rapid. Air that is in contact with the ground is chilled, and if there is a little wind to produce a TURBULENT FLOW that mixes the air, all the air to a height of a few hundred feet will grow cooler. Radiative cooling has little effect above this height, however, so air above the mixed layer remains at its daytime temperature. At the same time, WATER

VAPOR, CARBON DIOXIDE, and certain other atmospheric gases present in the air above the mixed layer absorb some of the outgoing infrared radiation. This absorption raises the temperature of the air, until by dawn the lowest layer of air is cooler than the air above it. As the Sun rises and the ground begins to warm again, the temperature of the lower air starts to rise and the warm air expands upward into the inversion layer. The overnight inversion then breaks down, and the usual LAPSE RATE is established.

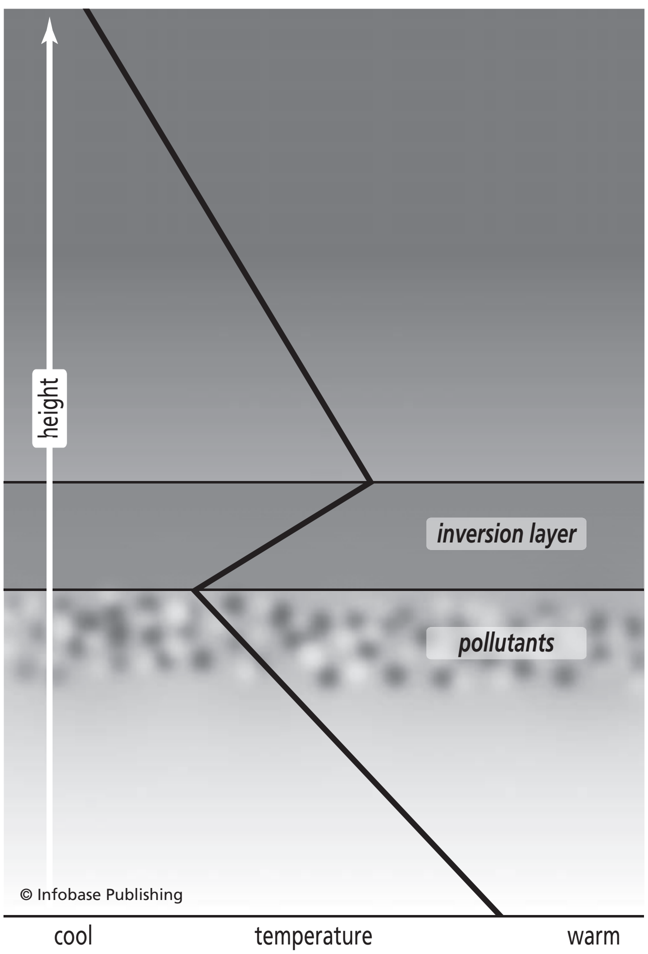
It is this type of inversion that develops over the tropical oceans. Here, though, it is not the surface that cools by radiation, but the air above it. Because of its high HEAT CAPACITY, the ocean surface does not cool at night. The air immediately above it is very moist, and water vapor emits infrared radiation. This cools the air to a height of about 1,700 feet (519 m), and although the air is being warmed by contact with the sea surface, the rate of cooling exceeds the rate at which the air is warmed. Above that height the air is drier, and so it loses less heat, forming an inversion.

Many inversions are caused by ADVECTION. An advectional inversion develops when cold air moves across a warm surface, undercutting air that had previously been warmed by contact with the surface. The warm air then lies above the cold air. Because the warm air is stable (*see* STABILITY OF AIR), it tends to return to its former level if it is made to rise. There is little mixing of the air, and the warm air lies like a blanket on top of the cooler low-level air.

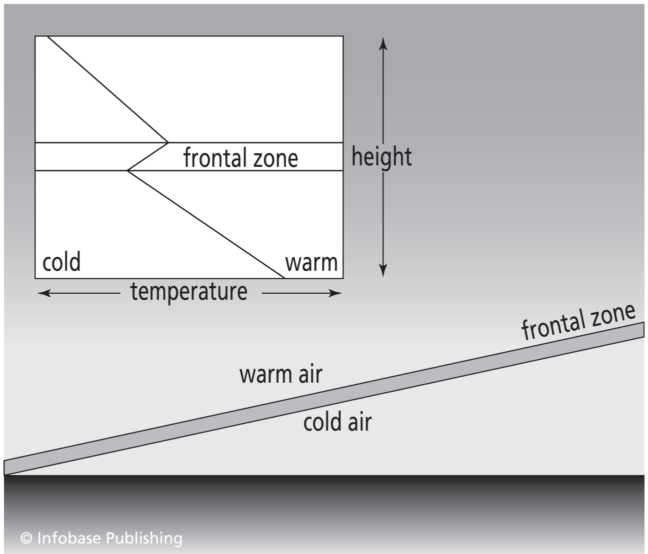
As the name implies, a frontal inversion most often occurs at a FRONT where warm air lies above cold air. Air temperature decreases with height from the surface to the frontal zone. There it increases with height owing to the transition from one AIR MASS to the other. The front therefore forms a barrier to air that is rising convectively in the cold air mass beneath it.

The most persistent inversions occur at the centers of ANTICYCLONES, where air is subsiding. As the air sinks, it is compressed and warms adiabatically (*see* ADIABAT). The subsiding air is unable to sink all the way to the surface, however, because turbulence in the lower air prevents it from doing so. This allows warm, subsiding air to form an inversion layer above the mixed air near to the surface. A high level inversion forms 1,000 feet (300 m) or more above the surface and is caused by the cooling of subsiding air in an anticyclone that occurs when the surface is much colder than the air. Above the chilled layer the air is warmer.

Trade wind inversions are of this type, and they form in the same areas of the Tropics as the low-level radiation inversions. Consequently, there are often two inversions, a radiation inversion at about 1,700 feet (519 m) and a trade wind inversion above it, at about 5,000–6,500 feet (1,500–2,000 m). There is a layer of mixed air beneath the lower inversion and another layer of mixed air between the two inversions. Mixing in the upper layer is driven by water vapor that rises by CONVECTION from the top of the lower inversion layer. Water vapor then condenses, releasing LATENT HEAT that increases the instability and mixing, and also forming cumulus clouds (*see* CLOUD TYPES).



Ordinarily, air temperature decreases with height. Sometimes the situation is reversed in a layer of air where the temperature increases with height. This is an inversion layer and air beneath it is trapped. Consequently, pollutants accumulate.



A frontal inversion occurs where warm air is held above a front, with cold air beneath it. This produces a temperature inversion in the frontal zone, where temperature increases with height.

The trade wind inversion is a fairly permanent feature of the high-latitude edges of the Hadley cells (*see* GENERAL CIRCULATION) at a height of 5,000–6,500 feet (1,500–2,000 m), the height increasing toward the equator. The increase in height occurs partly because subsidence decreases closer to the equator, reducing the supply of warm air, and partly because, as the lower air becomes increasingly moist and unstable, cumulus clouds frequently penetrate the inversion. The clouds evaporate in the dry air above the inversion, cooling it by the absorption of latent heat.

An inversion can inhibit PRECIPITATION. An inversion of this type, called a precipitation inversion or rainfall inversion, sometimes develops in mountain areas, but they are commonest in the Tropics, where they are associated with the Hadley cells. Subsiding air on the high-latitude sides of the Hadley cells warms adiabatically, and some of it forms warm pockets of dry air at a height of 50,000–65,000 feet (1.5–2.0 km) over the eastern sides of all the tropical oceans. These pockets restrict the vertical movement of air rising by convection, and this reduces the amount of condensation and consequent precipitation.

The lower stratosphere is also an inversion layer, and the tropopause, marking the boundary between the troposphere and stratosphere, is an inversion. Air that has risen in the INTERTROPICAL CONVERGENCE ZONE loses its moisture through adiabatic cooling and condensation. It descends as dry air and warms at the dry adiabatic lapse rate. Near the surface, air is flowing from higher latitudes toward the equator. This forms a layer of air that is cooler than the subsiding air. The cool lower layer is thus trapped beneath the inversion. This limits the vertical development of cloud, restricting the capacity of the surface air to lose the moisture it accumulates in its passage over the ocean.

The inversions that are so common over Los Angeles are usually caused by subsiding air at the eastern edge of the SUBTROPICAL HIGH that lies over the Pacific Ocean. Cool air moving from the ocean over the land intensifies these inversions by lifting the warmer air and forming a cool layer beneath it. The mountains to the east of Los Angeles prevent the pool of cool air from moving farther inland and weakening the inversion.

An inversion forms a cap over the air below it. Surface air cannot penetrate it to rise higher, and any pollutants carried by the air are trapped (*see* AIR POLLUTION). If the inversion persists for any length of time over a large city, pollutants accumulate in the air and air quality deteriorates, sometimes to a level that is harmful to health. The PHOTOCHEMICAL SMOG that afflicts many cities, including Athens, Mexico, Tehran, and Los Angeles, forms in air trapped beneath an inversion. It was smoke held beneath an inversion that mixed with FOG and caused the “pea-soupers” for which London and other industrial cities were once notorious and that culminated in the London smog incidents (*see* AIR POLLUTION INCIDENTS).

A capping inversion develops when a dry air mass advances against a moist air mass more slowly at ground level than it does above the PLANETARY BOUNDARY LAYER, at about 1,700 feet (519 m). This is usually due to the retardation of low-level air by surface FRICTION. The dry air overruns the moist air, preventing the development of convective clouds. Capping inversions are often associated with DRY LINES.

Although the term *inversion* is most often applied to an inversion of temperature, it can also describe the situation in which the HUMIDITY increases with height, rather than decreasing, which is more usual. An inversion of this kind is called a moisture inversion.

ion An atom or molecule that carries an electromagnetic charge because it has either lost or gained one or more electrons. An atom comprises a nucleus composed of protons, which carry positive electromagnetic charge, and neutrons, which carry no charge. A cloud of electrons surrounds the nucleus. Each electron carries negative charge that is equal to the charge on one proton.

Ordinarily, the negative charge on the electrons precisely balances the positive charge on the protons, so the atom has no net charge. Should the atom gain one or more electrons, however, it would have a net negative charge and would be a negatively charged ion, or anion, its charge indicated by as many superscripted minus signs as are needed to describe its charge, each sign representing one unit of charge. Were it to lose one or more electrons, it would become a positive ion, or cation, and its charge would be indicated by as many superscripted plus signs as necessary.

Atoms that do carry charge usually occur naturally in compounds formed by ionic bonds (*see* CHEMICAL BONDS) between positive and negative. For example, chlorine (Cl^-) bonds with sodium (Na^+) to form common salt (NaCl, sodium chloride) and with hydrogen (H^+) to form hydrochloric acid (HCl). The addition of electrons to an atom or the removal of ions from it is known as ionization.

Ionizing radiation is electromagnetic radiation that is capable of causing the ionization of atoms. In the atmosphere, photoionization is the ionization of an atom that occurs when it absorbs a photon of electromagnetic radiation with a wavelength of less than about 0.1 μm, which is in the ULTRAVIOLET part of the SOLAR SPECTRUM. Photoionization occurs in the region of the upper atmosphere known as the ionosphere (*see* ATMOSPHERIC STRUCTURE), where the density of the air is such that collisions between solar radiation and gas molecules are common. PHOTODISSOCIATION, the first step in photoionization, separates gas molecules into their constituent atoms ($O_2 \rightarrow O + O$; $H_2 \rightarrow H + H$). Individual atoms are then ionized to produce separate charged atoms and free electrons. This imparts an electrical charge to the ionosphere (hence its name) and it also absorbs photons of ultraviolet light. The radiation primarily responsible for ionizing atmospheric gases is solar radiation in the short-wave ultraviolet and long-wave X-ray wavelengths, of about 0.4–0.001 μm. COSMIC RADIATION also contributes to ionization.

iso- A prefix derived from the Greek word *isos,* meaning "equal," that is often attached to words describing lines drawn on a map or chart to link points where a particular quality has the same value.

A constant-pressure surface, also called an isobaric surface, is a surface across which the atmospheric pressure is everywhere the same. Although such a surface is level with respect to pressure, it is not level with respect to height above the land or sea surface. Consequently, the height of the constant-pressure surface can be shown by contours. Depressions in the constant-pressure surface correspond to areas of low pressure and raised areas to regions of high pressure.

An isallobar is a line that is sometimes drawn on a synoptic chart (*see* WEATHER MAP) to link places where the atmospheric pressure has changed by an equal amount during a specified period of time. It is usually based on data for the change in pressure over the preceding three hours that are included in every report from a weather station (*see* STATION MODEL). Isallobaric is an adjective that describes a constant or equal change in atmospheric pressure over a spatial distance or over a specified time.

An isallotherm is a line that is sometimes drawn on a synoptic chart to link places where the temperature has changed by the same amount over a specified period of time.

An isanomolous line or isanomal is a line that is drawn on a chart to link points where the value of a particular meteorological quantity varies from the regional average by the same amount, that is, to joint points of equal anomaly. The anomalies are adjusted for the effects of latitude and elevation. If the anomalous value is greater than the average the anomaly is said to be positive, and if it is lower than the average it is said to be negative. A place that is usually warmer than the surrounding area has a positive temperature anomaly; if the rainfall is usually lower than that of the surrounding area it has a negative rainfall anomaly.

An isobar is a line that is drawn on a map to join points where the atmospheric pressure is the same. Isobars resemble the contours on a physical map and are said to depict an isobaric surface. Those drawn on a map that also shows the land surface are usually corrected to their sea-level value. A map showing the actual surface pressure would reflect the elevation of the surface and would be very difficult to interpret meteorologically. Isobars do not necessarily refer to the sea surface, however, and isobaric charts can be drawn for any altitude.

An isobront is a line that is drawn on a map to link places at which THUNDERSTORMS reached the same stage of development at the same time.

An isodrosotherm is a line that is sometimes drawn on a synoptic chart to link places where the dew point temperature (*see* DEW) are the same.

An isogradient is a line that is drawn on a map to link places where the horizontal gradient of pressure or temperature is the same.

An isohel is a line drawn on a map that joins places which experience equal numbers of hours of sunshine.

An isohume is a line that is drawn on a map to link places of equal HUMIDITY across a specific surface. The measure used may be the relative humidity, specific humidity, or mixing ratio.

An isohyet is a line drawn on a map that joins places which receive the same amounts of rainfall.

An isokeraun or isoceraun is a line that is drawn on a map to link places that experience the same frequency or intensity of thunderstorms.

An isoneph is a line that is drawn on a map to link places that are equally cloudy.

An isonif is a line that is drawn on a map to link places that received equal amounts of snowfall.

An isopectic is a line that is drawn on a map to link places where winter ice begins to form at the same time.

An isophene is a line that is drawn on a map to connect places at which a particular stage in plant development (*see* PHENOLOGY) occurred on the same date. An isophene map for a certain event, such as the commencement of the wheat harvest, shows the rate at which that event advanced across a region.

An isopleth is a line or surface that is drawn on a map or chart to connect points that are equal in respect of some quantity, such as temperature or pressure. Isobars and isotherms are isopleths. Because of the stratification of the atmosphere, most isopleths are approximately horizontal.

An isopycnal is a line or surface that is drawn on a map or chart to connect points of equal air density. DENSITY is a more fundamental factor than TEMPERATURE in determining the behavior of air, and a baroclinic atmosphere is usually defined by the intersection of isobars and isopycnals.

An isoryme is a line that is drawn on a map to link places where the incidence of FROST is the same.

An isotach is a line drawn on a map that joins places that experience winds of the same speed.

An isothere is a line that is drawn on a map to link places where average summer temperatures are the same.

An isotherm is a line drawn on a map or TEPHIGRAM that joins points that are at the same temperature.

isoprene A volatile hydrocarbon compound (C_5H_8) that forms the structural base for many compounds synthesized by plants. Isoprene molecules form units that combine to form the larger molecules of a class of compounds called terpenes. Isoprene and terpenes are emitted by plants and especially deciduous trees.

Both isoprene and terpenes are highly reactive chemically and play an important part in the formation of OZONE in the lower atmosphere. In urban areas isoprene makes an important contribution to the formation of PHOTOCHEMICAL SMOG, and in rural areas it is the predominant hydrocarbon involved.

isotope One of two or more varieties of atom that all belong to the same element. The atoms possess identical chemical properties but differ in their relative atomic masses.

The chemical properties of an element are determined by the number of protons in the nuclei of its atoms. Protons carry positive electromagnetic charge that holds the electrons surrounding the nucleus, and it is this property that allows atoms to bond with other atoms (*see* CHEMICAL BONDS). All the isotopes of an element have atoms with the same number of protons in their nuclei, but differ because their nuclei contain different numbers of neutrons, which carry no charge and affect only the mass of the atom.

Most elements comprise two or more isotopes that occur naturally in constant proportions. Although all the isotopes of an element are chemically identical, the difference in their masses may affect aspects of their physical behavior. The OXYGEN isotopes that water molecules contain affect the evaporation of water, for example, and oxygen isotope ratios are used in studies of past climates.

isotropic Having properties that change independently of direction. The properties of an isotropic substance are the same regardless of the direction from which the substance is approached. On a small scale, of distances up to about 3 feet (1 m), the atmosphere is fairly isotropic, but on a large scale it is strongly anisotropic.

An anisotropic substance has properties that change in a particular direction. Consequently, the properties of an anisotropic substance vary according to the direction from which the substance is approached. On a large scale the troposphere (*see* ATMOSPHERIC STRUCTURE) is strongly anisotropic. Air TEMPERATURE and pressure decrease with height, and AIR PRESSURE decreases or increases along a horizontal gradient toward centers of low or high pressure.

J

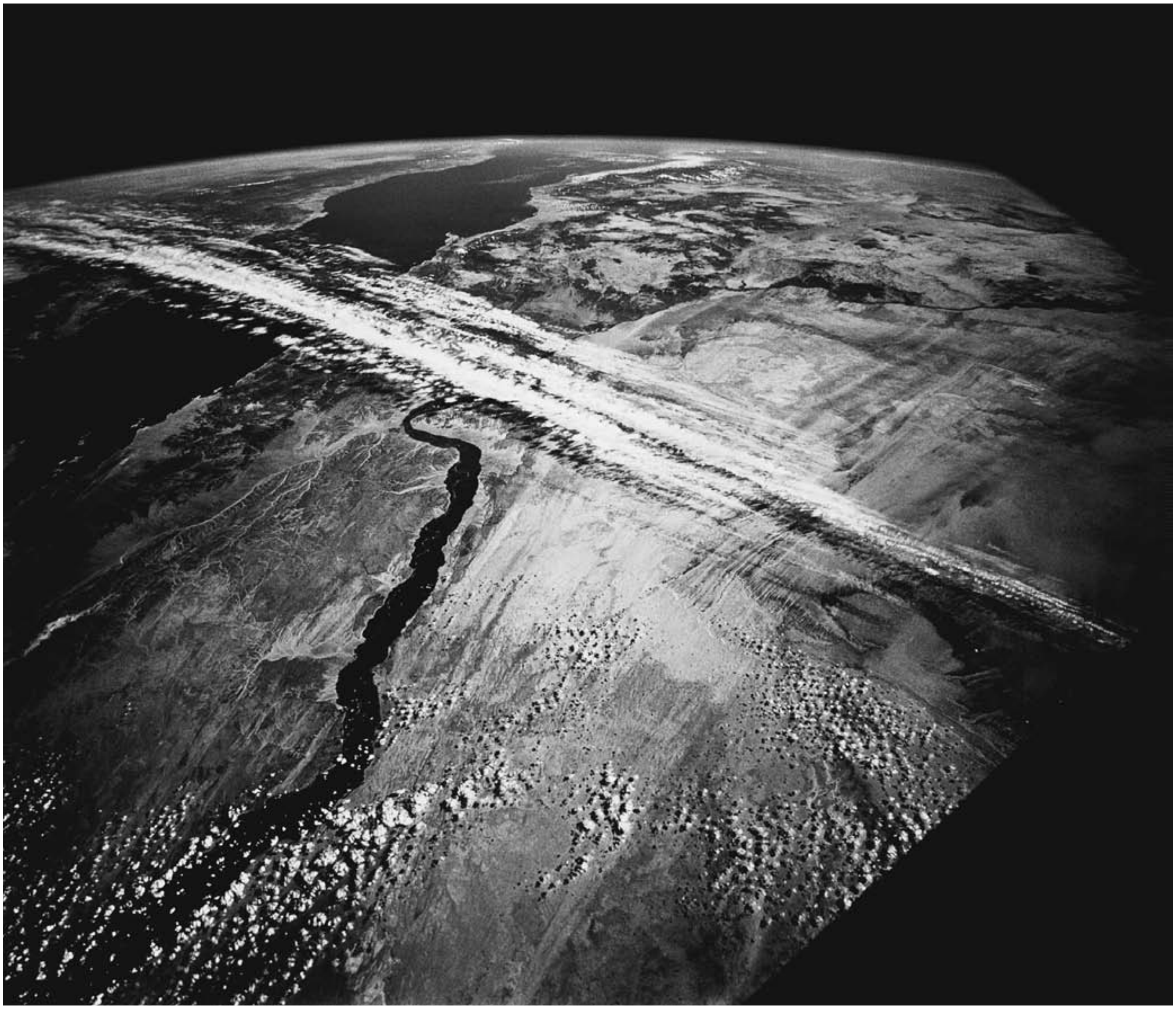
jet stream A winding ribbon of strong wind that is found close to the tropopause, in either the upper troposphere or lower stratosphere (*see* ATMOSPHERIC STRUCTURE). Typically, a jet stream is thousands of miles long, hundreds of miles wide, and several miles deep.

The existence of the jet stream was discovered during World War II. The crews of American aircraft flying at high altitude across the Pacific and of German aircraft flying in the Mediterranean region found their journey times sometimes varied greatly from those they had calculated using the winds predicted by meteorologists. Flying westward, crews sometimes found they were barely moving, but on eastward flights they traveled much faster than their predicted speed. Air crews came to realize that at their cruising altitudes they were encountering winds that blew irregularly along snaking paths with speeds comparable to those of their aircraft. They called these winds jet streams. If they approached the jet stream from above or below they found the wind speed increased by about 37–73 MPH for every 1,000 feet of altitude (18–36 km/h per 1,000 m). If they approached from the side it increased by the same amount for every 60 miles (100 km) of distance from the core of the jet stream. At the center of a jet stream—the core—the sustained wind speed averages about 65 MPH (105 km/h) but it sometimes reaches 310 MPH (500 km/h).

There are several jet streams. With one exception, they all blow from west to east in both hemispheres. In the Northern Hemisphere, the polar front jet stream is located between about 30°N and 40°N in winter and about 40°N and 50°N in summer. The subtropical jet stream is located at about 30°N throughout the year. In summer, there is also an easterly jet at about 20°N extending across Asia, southern Arabia, and into northeastern Africa. This is the only jet stream that blows from east to west. The Southern Hemisphere polar front jet stream is at about 45°S in summer, with two branches that spiral into it. One of these begins off eastern South America at about 32°S, and the other starts in the South Pacific at about 30°S 150°W. In winter, the two branches start from about 20°S, one from South America and the other from about 170°W, and the jet stream is at about 50°S. The Southern Hemisphere subtropical jet stream is at about 30°S.

The polar front jet stream is associated with the polar FRONT. There is a steep temperature gradient across the polar front, where tropical air and polar air meet (*see* AIR MASS). The gradient is at a maximum at the tropopause, where the jet stream occurs in the tropical air and, therefore, on the side of the front nearest to the equator. The wind at the core of the polar front jet stream can reach 95 MPH (150 km/h) in summer and 185 MPH (300 km/h) in winter.

The subtropical jet stream is the jet stream closest to the equator in both hemispheres. It is at about 30°N and S latitude throughout the year and is produced by a temperature gradient that occurs only in the upper troposphere. The subtropical jet stream is more persistent than the polar jet stream. Consequently, references to "the jet stream" usually relate to the subtropical jet stream, and it is this jet stream that is most often

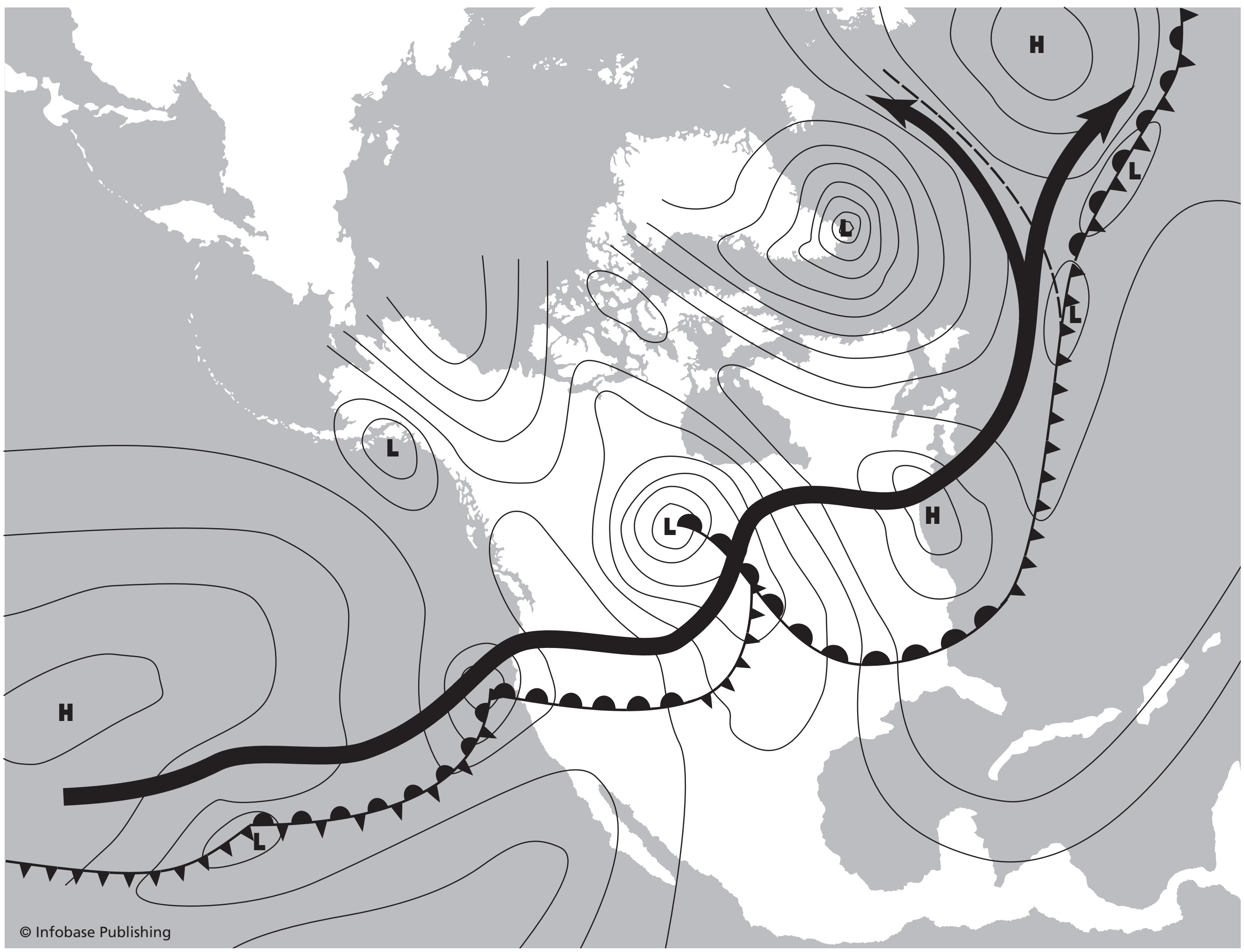


A line of clouds marks the position of the jet stream over Egypt and the Red Sea in this photograph taken from the *Gemini 12* spacecraft. The top of the Sinai Peninsula can be seen projecting into the Red Sea and the strip of vegetation marks the course of the River Nile. North is to the left. *(NASA)*

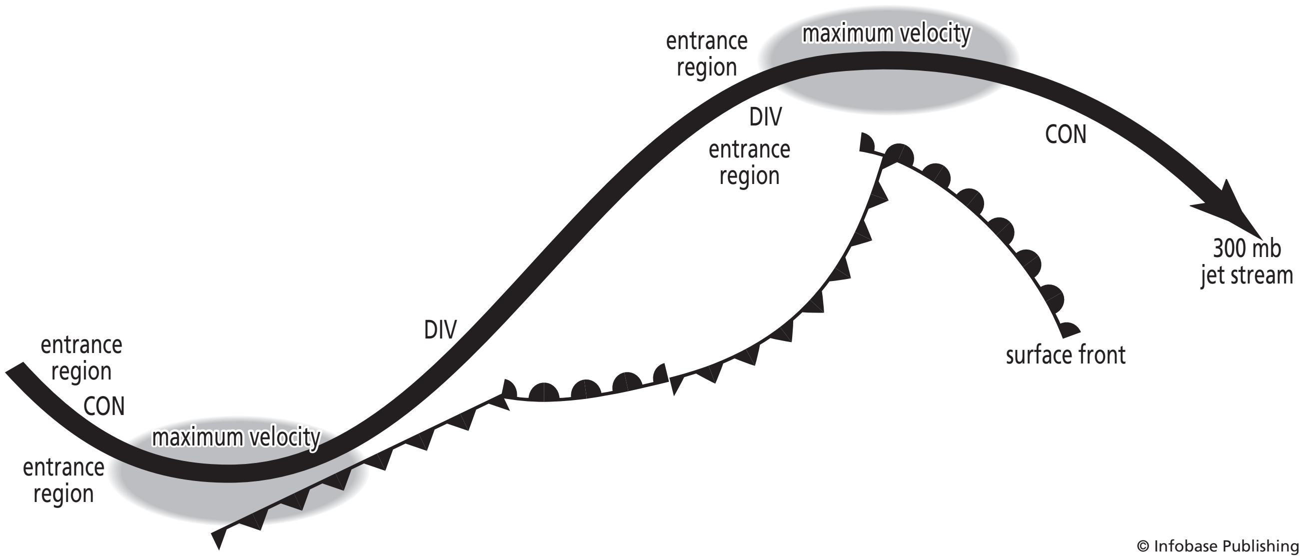
shown on maps. Its strength varies between summer and winter with the changing temperature gradient. In the Northern Hemisphere, its speed in winter is greatest over the Pacific Ocean, and it is greatest over North America in summer.

The easterly jet blows from east to west over India and Africa. The jet forms in summer in the upper troposphere at a height of about 9 miles (15 km) and extends from the South China Sea to the southeastern Sahara. In the summer, the equatorial TROUGH that is associated with the INTERTROPICAL CONVERGENCE ZONE (ITCZ) moves northward to about latitude 25°N. The THERMAL EQUATOR lies along the equatorial trough and to the south of the thermal equator, on the side nearest the equator, warm air is rising vigorously. There is cooler air throughout the troposphere between the thermal equator and the geographic equator. This situation produces a strong north–south pressure and temperature gradient, reversing the normal baroclinicity (*see* BAROCLINIC). The gradient is most marked at high level, where it generates a THERMAL WIND at about 15°N. Thermal winds blow with the cooler air on their left in the Northern Hemisphere. Consequently, this high-level thermal wind blows from east to west. The easterly jet reaches its maximum force in about July. In September, as the southwesterly MONSOON retreats from India, the thermal gradient weakens, the mid-latitude westerly winds move farther south, and a branch of the subtropical jet stream, blowing (from west to east) to the south of the Himalayas, replaces the easterly jet.

All jet streams are THERMAL WINDS. That is to say, they are produced by the large horizontal temperature gradients associated with baroclinicity. These gradients reach a maximum across major fronts, and especially across the polar and subtropical fronts, and the gradients increase with height. The steepest thermal gradient occurs at the top of the polar and subtropical fronts, close to the tropopause, which is where the jet streams are located. The AIR PRESSURE determines the precise altitude of the jet streams. The polar front jet stream occurs at about the 300 mb level and the subtropical jet stream at about the 200 mb level. The core of a jet stream lies on the warm side of the front, and the wind blows with the cold air on its left in the Northern Hemisphere and on its right in the



The position of the polar front jet stream across North America and the distribution of pressure and fronts associated with it. Entrance regions are linked to anticylones on the northern side and depressions on the southern side. Exit regions have depressions on the northern side and anticyclones on the southern side.

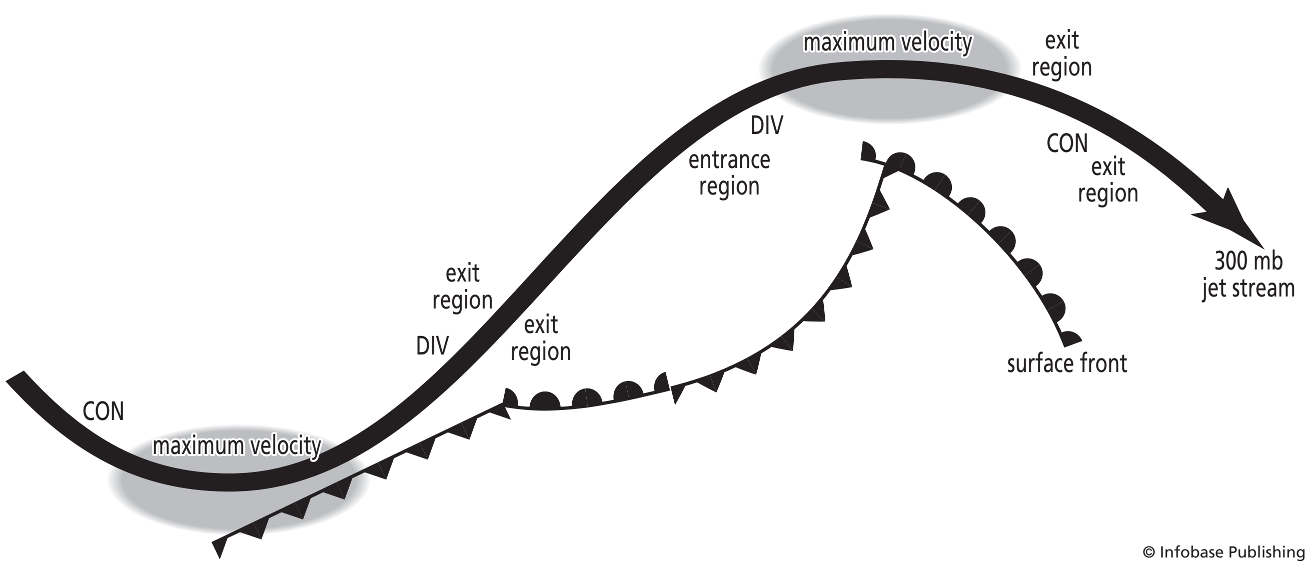


The entrance region lies on the upstream side of the core, where air is being drawn into the jet stream.

Southern Hemisphere, resulting in a westerly wind in both hemispheres.

The area in which air is being drawn toward the core of a jet stream is called the entrance region. Air entering from the side nearest the pole (the cold side) is subjected to convergence (*see* STREAMLINES) and subsides as convergence increases its density. Some of this air is drawn down from the lower stratosphere and the jet stream contains more OZONE (of stratospheric origin) than does the air adjacent to the jet stream but outside it. Air entering the core from the side nearest the equator (the warm side) is subjected to divergence and, as its DENSITY decreases, it tends to rise.

As air is drawn into the jet stream from the colder side it accelerates into a region of higher positive (cyclonic) VORTICITY. This increase in speed in a straight line is known as linear acceleration. As well as in the entrance region of a jet stream it occurs wherever air is accelerated in the direction of a wind. Winds entering the core region of a jet stream tend to be



The exit region lies on the downstream side of the core, where air is being expelled from the jet stream.

supergeostrophic (*see* GEOSTROPHIC WIND) and angled slightly across the isobars (*see* ISO-) toward the region of lower pressure. This is because the CORIOLIS EFFECT exceeds the PRESSURE GRADIENT FORCE and acts at an angle to it, so there is a component of the forces acting on the air in the direction of the wind.

It is in the core of a jet stream that wind speeds reach their maximum. There are regions within a jet stream, called jet streaks, where the wind speed is higher than it is elsewhere.

Acceleration causes the wind to become narrower horizontally, producing convergence, and it also sinks. High-level convergence produces a region of high surface pressure. The air then travels along the core and is expelled from the jet stream at an exit region.

The exit region is the area in which air is being expelled from the core of a jet stream. Air leaving on the side nearest the pole (the cold side) is subjected to divergence and tends to rise. Air leaving the core on the side nearest the equator (the warm side) is subjected to convergence and tends to subside. Air leaving the core on the cold-air side enters a region of lower positive vorticity, and there is high-level divergence with corresponding low-level low pressure. The pattern is reversed for air entering and leaving the core on the warm-air side, with divergence where the air is entering and convergence where it is leaving.

High-level divergence and convergence produce areas of high and low surface pressure. ROSSBY WAVES develop along the jet stream, causing it to change direction according to an index cycle (*see* ZONAL INDEX). The Rossby waves generate frontal systems (*see* FRONT) and their associated DEPRESSIONS, which travel with the generally westerly movement of mid-latitude air.

Jevons effect The effect on the measurement of rainfall that is caused by the RAIN GAUGE itself. In 1861 the English economist, logician, and scientist William Stanley Jevons (1835–82) discovered that the gauge disturbs the flow of air that passes it. Some of the air is deflected, carrying some raindrops with it, so the amount of rain captured by the gauge is smaller than the amount that falls on ground a short distance from the gauge. The effect is real, but too small to be of importance.

Joseph effect The tendency for a particular type of weather to persist and repeat itself. Heat waves (*see* WEATHER TERMS), DROUGHTS, and COLD WAVES are examples of persistence. Persistence is used in weather forecasting, when the forecaster predicts that the weather over the next few hours or days will remain as it is at present.

A short-range forecast that assumes persistence is often accurate, because in middle latitudes, where the weather is more changeable than it is elsewhere in the world, weather systems last for up to seven days. The tendency is known as the Joseph effect because of the dream that Pharaoh described to Joseph in the Book of Genesis: "Behold, there come seven years of great plenty throughout all the land of Egypt: And there shall arise after them seven years of famine" (Genesis 41, 29–30).

Jurassic A period of geologic time that followed the TRIASSIC period. It began 199.6 million years ago and ended 145.5 million years ago, with the commencement of the CRETACEOUS period. It was a time when invertebrate life flourished in the oceans and reptiles flourished both on sea and on land. The dinosaurs first appeared in the Middle Jurassic (175.6–161.2 million years ago) and *Archaeopterix lithographica,* the first bird but with several reptilian features, lived during the Late Jurassic (161.2–145.5 million years ago). Mammals also existed throughout the Jurassic.

The climate during the Jurassic was warmer and drier than the present global average climate. The average temperature was approximately 72°F (22°C), and there was no ice at either of the poles. The air contained an average 1,800 parts per million (ppm) of CARBON DIOXIDE compared with about 365 ppm today. *See* APPENDIX V: GEOLOGIC TIMESCALE.

juvenile water WATER that is formed by physical and chemical processes in the magma, which is the hot, plastic rock beneath the Earth's solid crust. Juvenile water has never been in the atmosphere or near the surface of the Earth, but it is released during volcanic eruptions.

A very large amount of juvenile water is present in the magma. A layer of magma with a volume of about 4 cubic miles (10 km^3) and a density of 2.5 (that is, 2.5 times the density of water) may contain about 2 billion (2×10^9) cubic feet (1.25×10^9 m^3) of water.

Water that falls from the sky as PRECIPITATION is called meteoric water, and water that was trapped when sediments were deposited and remains held inside sedimentary rocks is called connate water.

K

katabatic wind (drainage wind, fall wind, gravity wind) A cold wind that blows downhill across sloping ground. The word is from the Greek *katabatikos,* "going down."

The downhill flow of cold air under the influence of gravity is called air drainage.

A katabatic wind usually develops on a still, cold night when the ground cools by radiating the warmth it absorbed by day and the air is cooled from below by contact with the ground. An INVERSION may then develop, trapping a layer of cold air beneath a layer of warmer air. The cold air will then flow down any slope and accumulate in hollows and valleys. If the katabatic wind is very gentle, allowing the accumulating air to become static in a hollow that is shaded from the afternoon Sun, FROST can develop and the hollow is known as a frost hollow.

A mountain breeze is a katabatic wind that blows at night in some mountain regions. It most commonly occurs when conditions are calm and the sky is clear and it is more frequent in winter. Mountainsides where mountain and valley breezes (*see* WIND SYSTEMS) occur regularly are often preferred for growing fruit, because the constant air movement prevents the static conditions in which frost can form.

Katabatic winds also occur over the polar ICE SHEETS, which are domed, with the highest elevation at the center. Along the coast of Antarctica, the average katabatic wind speed is about 45 MPH (72 km/h), and BLIZZARDS of blowing snow are common.

A sastruga is a wave in the snow and ice of Antarctica that forms where the katabatic winds blow constantly. Sastrugi are aligned parallel to the wind. They are usually about 2 inches (5 cm) high, but in places they can be more than 6 feet (1.8 m) high.

A mountain breeze results from a circulation of air that produces a cool wind, which flows down the side of a mountain at night.

Kelvin waves Ocean waves that occur only in equatorial waters. Their amplitude is measured in tens of meters at the THERMOCLINE and their wavelength (*see* WAVE CHARACTERISTICS) in thousands of meters. They take about two months to cross the Pacific and because of the CORIOLIS EFFECT they are higher on the side closest to the equator. They are associated with El Niño events (*see* ENSO). The waves are named after the Scottish physicist Lord Kelvin (William Thomson, 1824–1907), who discovered them.

kinetic energy The energy of motion, which is usually defined in terms of the amount of work a moving body could do if it were brought to rest. It is equal to $mv^2 \div 2$, where *m* is the mass of the moving body and *v* is its speed. For a rotating body, such as the air in a TROPICAL CYCLONE or TORNADO, the kinetic energy is equal to $I\omega^2 \div 2$, where ω is the angular VELOCITY and *I* is the MOMENT OF INERTIA. Kinetic energy is one of the two forms of energy, the other being POTENTIAL ENERGY.

Kirchhoff's law A law stating that the amount of radiation of a particular wavelength (*see* WAVE CHARACTERISTICS) that is emitted by a body is equal to the amount absorbed by that body at the same wavelength. This is expressed as

$$\varepsilon\lambda = \alpha\lambda f(\lambda,T)$$

where ελ is the EMISSIVITY at a stated wavelength, αλ is the absorptivity (*see* ABSORPTION OF RADIATION) at the same wavelength, and $f(\lambda,T)$ is a function that varies with the wavelength (λ) and surface temperature (*T*), but not with the material of which the surface is composed. The law means that if a body is a good or poor absorber of radiation it will be an equally good or poor emitter of radiation at the same wavelength.

The law was first described in 1859 by the German physicist Gustav Robert Kirchhoff (1824–87; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). From this law he went on to derive the concept of a perfect BLACKBODY. Although the Scottish physicist Balfour Stewart (1828–87) had reached a similar conclusion in 1858, Kirchhoff presented it more persuasively and is usually given the credit for its discovery.

Köppen climate classification A system for categorizing climates generically according to their temperatures and aridity that was devised by Wladimir Peter Köppen (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). Of all the schemes for CLIMATE CLASSIFICATION, Köppen's is the one most widely used by geographers.

Köppen began by relating climate to the plant growth in a region and to the type of vegetation present there. He was not the first scientist to note that particular plants grow only in certain places, and the distribution of vegetation types had already been mapped and described. Köppen worked from the map prepared by the Swiss botanist Alphonse-Louis-Pierre-Pyramus de Candolle (1806–93), the Professor of Natural History at the University of Geneva and possibly the most eminent botanist of his day. (His father had held the same position before him and was equally distinguished, mainly for his classification of plants.) Candolle published *Géographie botanique raisonée* (Botanical geography classified) in 1855 and *La Phytographie* in 1880. Phytogeography (its English name) is the scientific study of the geography of plant distribution). In 1874, Candolle produced a world vegetation map in which plant distribution was linked to the physiological structure of the plants. Köppen used this to define climates according to the zones occupied by particular vegetation types, producing his first climate map in 1884. He then developed this into a complete classification scheme for climates, publishing the first version in 1900 and the final version in 1936. Toward the end of his life, Köppen collaborated with the German climatologist Rudolf Geiger, who continued to work on modifications to the classification after Köppen's death.

The scheme is fairly complex and uses a code of letters to designate climatic details. Climates are grouped in six major categories, identified as A to F, all but one of which (B) are identified by temperature:

A. Tropical rainy climates in which the temperature in the coldest month does not fall below 64.4°F (18°C)
B. Dry climates
C. Warm temperate rainy climates in which temperatures in the coldest month are between 26.6°F (-3°C) and 64.4°F (18°C) and in the warmest month temperatures are higher than 50°F (10°C)
D. Cold boreal forest climates in which temperatures in the coldest month are below 26.6°F (-3°C) and temperatures in the warmest month are above 50°F (10°C)
E. Tundra climate in which temperatures in the warmest month are between 32°F (0°C) and 50°F (10°C)
F. Perpetual frost climate in which temperatures in the warmest month remain below 32°F (0°C)

The temperatures were chosen for particular reasons. Trees do not grow where the average summer temperature is below 50°F (10°C), for example, and some plants will not grow where the winter temperature falls below 64.4°F (18°C). A mean annual temperature of 26.6°F (-3°C) implies frost and probably some snow.

These principal categories are then divided further, mainly according to the amount and distribution of precipitation they receive.

Af climates are hot and rainy throughout the year.
Am climates are hot and excessively rainy in one season.
Aw climates are hot and in winter are dry.
BSh climates are semi-arid and hot.
BSk climates are semi-arid and cool or cold.
BWh climates are those of hot deserts.
BWk climates are those of cool or cold deserts.
Cfa climates are mild in winter, hot in summer, and moist throughout the year.
Cfb climates are mild in winter, warm in summer, and moist throughout the year.
Cfc climates are mild in winter, have a short, cool summer, and are moist throughout the year.
Cwa climates are mild in winter, hot in summer, and have dry winters.
Cwb climates are mild in winter, have short, warm summers, and are dry in summer.
Csa climates are mild in winter and hot and dry in summer.
Csb climates are mild in winter and have a short, warm, dry summer.
Dfa climates are very cold in winter, have a long, hot summer, and are moist throughout the year.
Dfb climates are very cold in winter, have a short, warm summer, and are moist throughout the year.
Dfc climates are very cold in winter, have a short, cool summer, and are moist throughout the year.
Dfd climates are extremely cold in winter, have a short summer, and are moist throughout the year.
Dwa climates have a very cold, dry winter, and long, hot summer.
Dwb climates have a very cold, dry winter, and a cool summer.
Dwc climates have a very cold, dry winter, and a short, cool summer.
Dwd climates have an extremely cold winter, and a short, moist summer.
ET is a polar climate with a very short summer.
EF is a climate of perpetual frost and snow.

In addition to these categories, additional letters are used to add further qualifications:

a Mean temperature in the warmest month is about 71.6°F (22°C).
b Mean temperature in the warmest month is below 71.6°F (22°C) and there are at least four months during which the mean temperature is higher than 50°F (10°C).
c There are between one and four months when the mean temperature is higher than 50°F (10°C), and the mean temperature does not fall below -36.4°F (-38°C) in the coldest month.
d The mean temperature in the coldest month is lower than -36.4°F (-38°C).
f Precipitation is sufficient for healthy plant growth in all seasons.
g The temperature is highest prior to the summer rainy season.
h The mean annual temperature is higher than 64.4°F (18°C).
i The climate is isothermal, which means there is less than 14°F (5°C) difference in mean temperature between the warmest and coolest months.
k Winters are cold, the mean annual temperature is below 64.4°F (18°C), and the mean temperature in the warmest month is higher than 64.4°F (18°C).
k′ This is similar to k, but in the warmest month the mean temperature is below 64.4°F (18°C).
l The mean temperature in all months is between 50°F (10°C) and 71.6°F (22°C).
m There is a short, dry season and heavy rain throughout the remainder of the year.
n Fog is frequent.
n′ Fog is infrequent, but the humidity is high although rainfall is low. The mean summer temperature is below 74.2°F (24°C).
p Conditions are similar to those in n′, but the mean temperature in one summer month is between 74.2°F (24°C) and 82.4°F (28°C).
p′ Conditions are similar to those in n′, but the mean summer temperature is higher than 82.4°F (28°C).
s There is a dry season in summer.
u The coldest month comes after the summer solstice.
v The warmest month is in the autumn.

w Winters are dry and rainfall during the remainder of the year is not sufficient to make good the deficiency, so plant growth is restricted.
w′ There is a rainy season in autumn.
w″ There are two distinct rainy seasons and two distinct dry seasons.
x Maximum rainfall occurs in spring or early summer and the late summer is dry.
x′ Conditions are similar to those of x, but there are infrequent, heavy falls of rain in all seasons.

krypton (Kr) A colorless gas that is present in the air in trace amounts (*see* ATMOSPHERIC COMPOSITION). It is one of the NOBLE GASES with atomic number 36, relative atomic mass 83.80, DENSITY (at sea-level pressure and 32°F, 0°C) 0.0000021 ounces per cubic inch (0.0000037 g/cm^3). Krypton melts at -250°F (-156.6°C) and boils at -242.1°F (-152.3°C).

L

Labor Day storm A hurricane (*see* TROPICAL CYCLONE) that struck southern Florida on Monday September 2, 1935—Labor Day. The maximum sustained wind speed was 185 MPH (298 km/h), and the central pressure fell to 892 mb. This made the storm category 5 on the SAFFIR/SIMPSON HURRICANE SCALE. Its central pressure was the lowest surface pressure recorded in the Western Hemisphere until hurricanes Gilbert (888 mb) in 1988 and Wilma (882mb) in 2005, although an unconfirmed report claimed a core pressure of 880 mb.

A train with 10 cars, sent to rescue a party of World War I veterans who were building a road bridge at Upper Keys, was washed off the track by the storm surge. At least 423 people died in the Labor Day storm, 164 residents and 259 veterans working on the bridge.

Lake Bonneville A lake that formed in what is now Utah about 32,000 years ago and finally disappeared about 14,000 years ago, during the Wisconsinian GLACIAL PERIOD (*see* APPENDIX VII: PLIOCENE, PLEISTOCENE, AND HOLOCENE GLACIALS AND INTERGLACIALS). At its greatest extent the lake was about 325 miles (523 km) long and 135 miles (217 km) wide, and had a surface area of about 19,000 square miles (49,200 km^2). In places it was more than 1,000 feet (305 m) deep and what are now mountains projected above the surface as islands.

During the Wisconsinian the average temperature was about 11°F (6°C) cooler than that of today and the climate was wetter. The lake was filled by water from PRECIPITATION, rivers, and the melting edges of GLACIERS. As the climate changed and most of the lake evaporated, the precipitation of salt formed the Bonneville salt flats. Modern Utah Lake is a freshwater remnant of Lake Bonneville and the Great Salt Lake, Little Salt Lake, and Sevier Lake are salt-water remnants.

Further Reading

Utah Geological Survey. "Commonly Asked Questions About Utah's Great Salt Lake and Lake Bonneville." Available online. URL: www.ugs.state.ut.us/online/PI-39/. Accessed December 27, 2005.

lake breeze A wind that is produced when air warms over land and rises by CONVECTION, and its place is taken by cool, moist air drawn from over the surface of a lake. This can bring a change in wind direction and a sharp fall in temperature over land adjacent to the lake shore. The breeze develops during the afternoon, by which time the land has been warmed, and is similar to a sea breeze (*see* LAND AND SEA BREEZES). In summer, when the difference between land and lake-surface temperatures is most extreme, the movement of cool, moist air beneath warm, dry air produces a front that can trigger THUNDERSTORMS.

lake effect A modification in the characteristics of air as it crosses a large expanse of water that is entirely enclosed by land. In summer, hot, dry, continental air (*see* AIR MASS) is cooled by contact as it crosses the open water surface and a large amount of water evaporates into it. Consequently, the weather on the LEE side of the lake is somewhat cooler and more humid than that on the opposite side and the rainfall is greater over high ground.

Lake-effect snow is SNOW that falls in winter on the lee side of a large lake, which is entirely enclosed by a large land mass. In most winters lake-effect snow falls very heavily to the east of the Great Lakes. Cold, dry, continental air travels across North America from west to east. When it reaches the Great Lakes, it makes contact with the surface of water that remains liquid for most of the winter and in some years does not freeze at all. The air is warmed a little by contact with the water and large amounts of water evaporate into it. When it reaches the other (eastern) side of the lakes, the air crosses land that is much colder. The air is chilled, its water vapor condenses, and there are heavy falls of snow. Places in what is known as the snow belt receive much more winter snow than places to the west of the lakes and accumulations of 2 feet (50 cm) in 24 hours are not uncommon. When the lakes freeze over, the effect ceases.

The snow belt comprises the strip of land up to about 50 miles (80 km) wide parallel to the lee shore of a large lake where winter snowfall is markedly higher than it is on the opposite, upwind side of the lake. Parts of Michigan, New York State, and Ontario, to the lee of the Great Lakes, receive up to three times more snow than regions in the same latitude but a long way from the lakes.

Lambert's law A law stating that the intensity of the radiation emitted in any direction from a unit surface area of a radiating body varies according to the cosine of the angle between the direction of the radiation and a line perpendicular to the radiating surface. The law was discovered by the German mathematician Johann Heinrich Lambert (1728–77), who was the first person to measure light intensities accurately and who coined the term *ALBEDO* (Latin for "whiteness"). A unit of luminance was named the lambert (L) in his honor. It is equal to one lumen per square meter, but is no longer in use. (*See* APPENDIX IX: SI UNITS AND CONVERSIONS.)

Lamb's classification A catalog of the type of weather conditions experienced over the British Isles every day from January 1, 1861 until February 3, 1997. The catalog was compiled by Professor H. H. Lamb (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) and ended when his final illness made it impossible for him to continue working on it. The catalog describes the direction in which the weather systems are moving, broken into eight directions (N, NE, E, SE, S, SW, W, and NW), and then classifies the systems as CYCLONIC, ANTICYCLONIC, or unclassifiable.

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Lamb's dust veil index (dust veil index, DVI) A set of numerical values which quantify the climatic effect of dust that is ejected into the atmosphere by a volcanic eruption. After an eruption, air movements disperse volcanic dust until it forms a thin veil covering a large area. This veil reflects a proportion of the incoming solar radiation and therefore exerts a climatic cooling effect at the Earth's surface. There is little exchange of air across the tropopause, and if the dust is injected into the stratosphere (*see* ATMOSPHERIC STRUCTURE) the veil may endure for several years before finally dispersing.

The index was compiled by Professor H. H. Lamb (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), based on his study of historical records from 1500 until 1983. Lamb then calibrated the resulting values, relating them to the 1883 eruption of Krakatau, to which he allotted a DVI value of 1000. The full index lists the name of each erupting volcano, the year it erupted, its latitude and longitude, the maximum extent of the veil of dust it emitted, the duration of the dust veil, the DVI value for the entire world, the DVI value for the Northern Hemisphere, and the DVI value for the Southern Hemisphere. Lamb calculated the effect of the dust veil by comparing the recorded surface temperature with the average temperature for the same place at the same time of year. He also used estimates of the amount of material ejected during each eruption.

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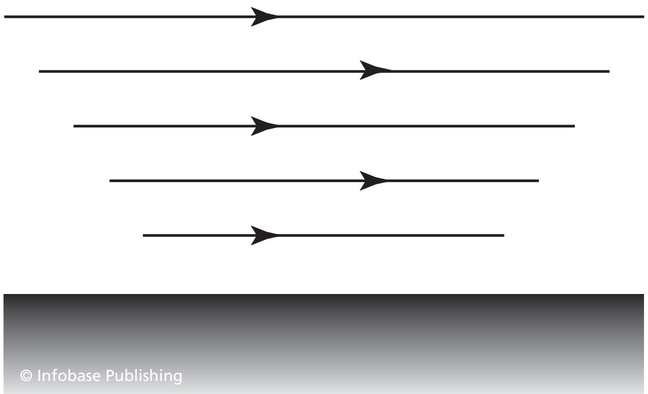


Laminar flow is a movement of a fluid in which all of the stream lines are parallel to one another.

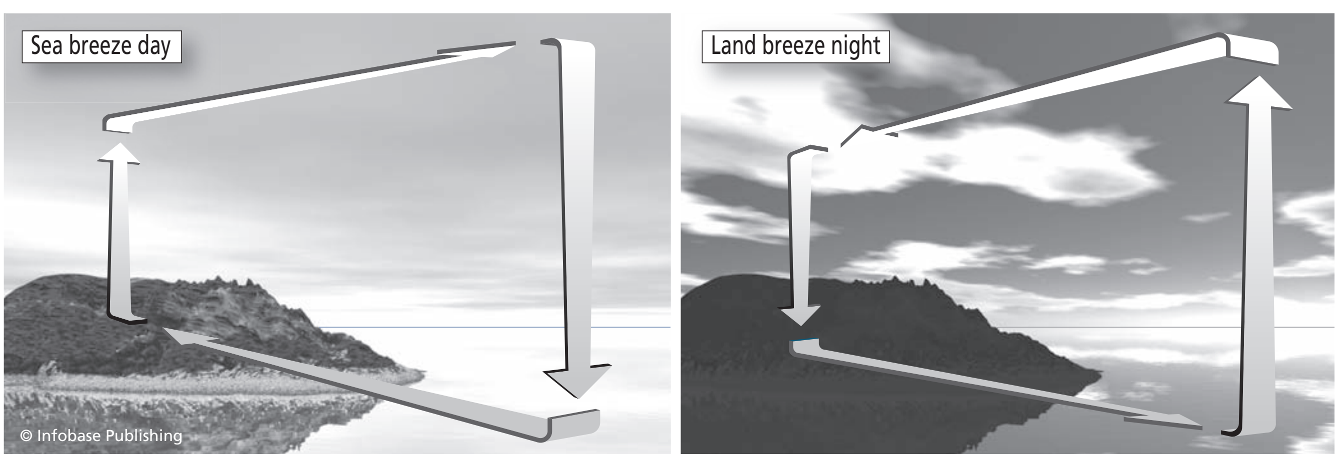
laminar flow The motion of a fluid that occurs smoothly, the fluid (air or water) forming sheets that lie along streamlines that are parallel to each other. Where the flow is laminar, the properties of the fluid at one level can be transferred to another level only through the random motion of molecules.

Laminar flow changes to turbulent flow when the speed reaches a value that is directly proportional to the viscosity of the fluid and inversely proportional to its density. This is because friction increases with flow speed, increasing in turn the difference in speed from one laminar sheet to another and thus transferring the effect of friction throughout the flow. Consequently, the movement of air is almost always turbulent, except very close to the ground surface. There a layer of air that is never more than a few millimeters thick (1 mm = 0.04 inch) adheres to the surface. This is called the laminar boundary layer and within it heat, momentum, and substances such as molecules of water vapor travel vertically only through random molecular motion.

land and sea breezes Winds that blow in coastal regions and along the shores of large lakes. In middle latitudes they are most common in fine weather in summer. In the Tropics, where seasonal temperature differences are less pronounced, coastal winds of this type can occur at any time of year.

During the morning, the land is warmed by the Sun and its temperature rises. The Sun also shines on the water, but its temperature changes much more slowly, because water has a much higher heat capacity than land. Air over the land is warmed by contact with the ground surface. The air expands and rises, drawing cooler air from over the water to replace it. This establishes a convection cell in which air rises over land, moves over the water at high level, sinks over the water, and flows back toward the land at low level. The cell is shallow, extending to no more than about 3,500 feet (1,070 m).

The wind flowing from the water to the land is a sea or lake breeze. It usually begins in the late morning and reaches a maximum in the middle of the afternoon, when the air temperature is highest. The wind speed can reach about 12 MPH (20 km/h) in a sea breeze, but less in a lake breeze. In the case of sea breezes, a sea-breeze front may develop.



During the day, warm air rises over the land and cool air flows from the sea to replace it. This is the sea breeze. At night, the land cools. If its temperature falls below that of the sea surface, air flows from land to sea as a land breeze.

Sea breezes are gusty and bring cool, moist air over the coast, reducing the temperature by up to 18°F (10°C). In the Tropics, sea breezes produce a cool coastal belt that extends up to 100 miles (60 km) inland. In middle latitudes the effect of sea breezes is seldom felt more than about 20 miles (32 km) inland from seacoasts and a shorter distance from lakeshores. Moist air crossing warm land can become unstable (*see* STABILITY OF AIR), leading to the formation of cumuliform cloud (*see* CLOUD TYPES) and showers.

At night the opposite effect occurs. The land cools more rapidly than the water, chilling the air in contact with it. This causes air to subside over the land, drawing air from over the sea to replace it at high level. Cool air flows from the land toward the sea at low level. This is the land breeze. The cell producing it is shallower than the one that produces a sea or lake breeze and the land breeze is weaker. It does not develop at all unless the land cools to below the temperature of the water surface.

The frequent movement of frontal systems often produces winds that obscure land and sea breezes in middle latitudes.

Landsat A satellite observation program that was designed by the National Aeronautics and Space Administration (NASA), in collaboration with the Department of Agriculture, Department of Commerce, and an Environmental Sciences Group within the Environmental Sciences Services Administration (which subsequently became the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION). The U.S. government funds the program, and the satellites are operated by the Department of the Interior and NASA. The aim of the program is the REMOTE SENSING of the Earth's resources. This includes studies of weather systems and climates.

Planning commenced in 1965, and the first satellite was launched on July 23, 1972. It was called the Earth Resources Technology Satellite 1 (ERTS 1). The name of the program and the satellites was changed to Landsat in 1975. *Landsat 1* (ERTS 1) ended its service on June 1, 1978. *Landsat 2* was launched on January 22, 1975, and was taken out of service on February 25, 1982. *Landsat 3* operated from March 5, 1978, until March 31, 1983. *Landsat 4* was launched on July 16, 1982, and its active life ended when it ceased transmitting data in August 1993. *Landsat 5* was launched on March 1, 1984, and is still functioning. *Landsat 6* operated from October 5, 1993, but failed to reach orbit. *Landsat 7* was launched on April 16, 1999.

All the Landsat satellites operate in polar ORBITS. *Landsats 1–3* orbited at an altitude of 570 miles (917 km), passing over every point on the surface at intervals of 18 days. *Landsats 4–7* orbit at 438 miles (705 km) and overfly every point at intervals of 16 days.

Further Reading

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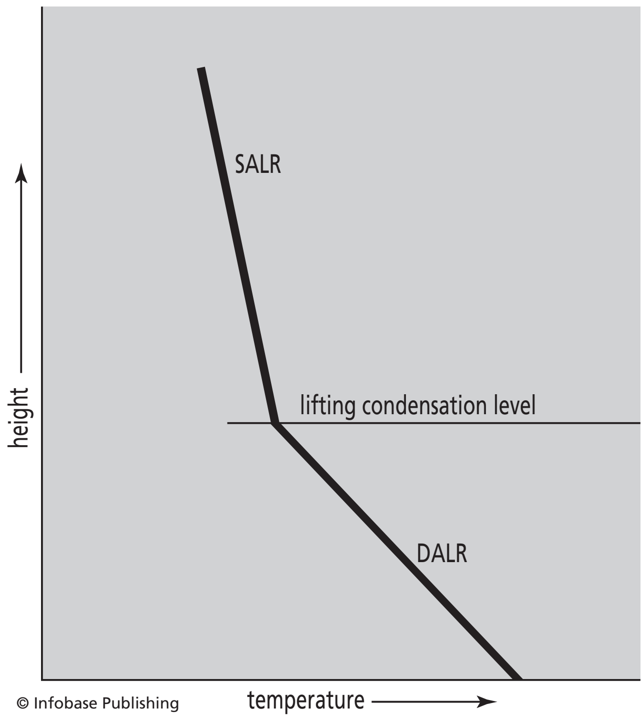
lapse rates The rates at which the temperature of a rising PARCEL OF AIR decreases with increasing height. This cooling is said to be adiabatic (*see* ADIABAT), which means it involves no exchange of heat with the air surrounding the parcel. Air can descend as well as rise. If it does so it will warm rather than cool and its rate of warming will also be equal to the lapse rate.

As it rises, the atmospheric pressure exerted on a parcel of air decreases. The parcel expands and the air temperature decreases, because the air molecules expend energy in pushing aside the molecules in the surrounding air. The rate at which the air temperature decreases is proportional to the specific heat of air and to the change in pressure. The specific heat of air (the amount of heat that is required to change the temperature of a given volume by a given amount) is constant and so is the change of pressure with height. Consequently, the rate of temperature change with height is also constant. This is known as the dry adiabatic lapse rate (DALR), and it is equal to 5.38°F for every thousand feet (9.8°C/km).

Most air contains some moisture, however, and when the parcel of air reaches the lifting condensation level (*see* CONDENSATION) the water vapor that the air carries will start to condense into liquid droplets. Condensation releases LATENT HEAT. This warms the air and partially offsets the rate of cooling. While water vapor is condensing, therefore, the air will cool at a slower rate, known as the saturated adiabatic lapse rate (SALR).

Calculating the lifting condensation level is simple. The wet-bulb depression (*see* THERMOMETER) is obtained by subtracting the wet bulb temperature from the dry



The lapse rate is the amount by which the temperature of a rising parcel of air decreases with altitude (and increases with descent). There are several lapse rates, of which the most widely used at the dry adiabatic lapse rate (DALR) and saturated adiabatic lapse rate (SALR). These separate at the lifting condensation level.

bulb temperature and the dew point temperature (*see* DEW) can then be calculated or read from a published table. Applying the DALR to the dry bulb temperature then gives the lifting condensation level, which is the height of the CLOUD BASE.

Unlike the DALR, the saturated adiabatic lapse rate is not the same under all conditions. It varies according to the temperature of the air. This is because the temperature determines the amount of water vapor the air can hold and, therefore, the amount of condensation that occurs. In very warm air, the SALR may be as low as about 2.7°F per 1,000 feet (5°C/km), but at an air temperature of -40°F (-40°C) it is about 5°F per 1,000 feet (9°C/km). An average value is about 3°F per 1,000 feet (6°C/km). The value of the SALR also varies very slightly with height, because more latent heat is emitted and absorbed through condensation and EVAPORATION at high temperatures than at low temperatures. This is because the lower the temperature the less water vapor the air can hold and, therefore, the amount of vapor available to condense or evaporate decreases with decreasing temperature.

Throughout the lower and middle troposphere (*see* ATMOSPHERIC STRUCTURE) a value of 2.75°F per 1,000 ft (5°C/km) for the SALR is sufficiently accurate for most purposes, but in the upper troposphere the SALR increases, approaching more closely to the DALR.

The standard lapse rate, often simply called the lapse rate, is calculated from the average temperature at the surface and at the tropopause, at a height of 36,000 feet (11 km). These temperatures are 59°F (15°C) and -70°F (-56.5°C) respectively, giving a lapse rate of about 3.6°F per thousand feet (6.5°C/km). This is very approximate, however, and varies with height, location, and season.

The global average lapse rate is about 1.1°F per thousand feet (2°C/km) between the surface and about 6,500 feet (2 km). It is 3.3°F per thousand feet (6°C/km) between 13,000 feet and 20,000 feet (4–6 km), and 3.8°F per thousand feet (7°C/km) between 20,000 feet and 26,000 feet (6–8 km). The lapse rate is usually smaller in winter than in summer; in continental interiors the winter lapse rate is sometimes negative; and the air at the top of a mountain may be warmer than the air in the valley below. Over subtropical and tropical deserts the summer lapse rate can exceed 4.4°F per thousand feet (8°C/km).

An additional lapse rate must be taken into account, however. The rate of condensation and evaporation is affected by the atmospheric pressure and, consequently, the dew point temperature decreases with increasing height by about 0.55°F for every thousand feet (1°C/km). This is known as the dew point lapse rate.

The rate at which the air temperature decreases with height as this is measured at a particular time and place is called the environmental lapse rate (ELR). This temperature change is not the result of adiabatic cooling, but simply the actual temperature that is observed, and it is very variable. Strong daytime heating of the ground may produce a layer of very warm air with much cooler air above it and a steep ELR. During the evening, the ground cools and the ELR becomes less steep. It may even reverse, with warmer air lying above cooler air producing a temperature INVERSION. If the ELR is greater than the dry adiabatic lapse rate, it is said to be superadiabatic.

The difference between the adiabatic lapse rate and the ELR is called the potential temperature gradient. If the two are the same, the potential temperature gradient will be zero and a rising parcel of air will have a constant BUOYANCY. If the adiabatic lapse rate is the larger, the gradient will be negative and the buoyancy of a rising parcel of air will increase with height. If the ELR is the larger, the gradient will be positive and the parcel of air will become less buoyant with height, eventually reaching a level at which its buoyancy is zero. An atmosphere in which the ELR is equal to the DALR is called a neutral atmosphere. This condition results from convectional instability. Convection tends to redistribute heat until the two lapse rates equalize. Differences between the DALR, SALR, and ELR determine whether or not a parcel of air is stable (*see* STABILITY OF AIR).

A curve on a graph that shows the change of temperature with height in the free atmosphere (*see* PLANETARY BOUNDARY LAYER) is called a lapse line.

Larsen ice shelf The ICE SHELF that extends from the eastern coast of the Antarctic Peninsula between 65° and 66°S, 60° to 62°W, covering several offshore islands. The peninsula extends northwestward from the mainland of Antarctica and forms the southwestern boundary of the Weddell Sea. Its covering of ice and the SEA ICE that surrounds it make the peninsula appear wider than it is; in fact it is a narrow strip of land with many offshore islands.

The Larsen is one of the smaller of the Antarctic ice shelves, as well as being the most northerly, the whole of it lying outside the Antarctic Circle (66.5°S). Scientists divide the Larsen Ice Shelf into four sections labeled A through D. Larsen A is the most northerly section with Larsen B to its south.

Summer temperatures at the northern end of the peninsula have risen by about 4.5°F (2.5°C) since 1940, and summers have lengthened from about 50 days to 80. Over the same period the extent of the sea ice off the peninsula has decreased by about 20 percent. The higher temperatures have allowed pools of water up to 0.5 mile (1 km) wide to lie on the surface of the ice. Liquid water drained from these pools into fractures, called crevasses, in the ice, weakening the ice at the bottom. Slowly, over the years, Larsen A grew weaker. Until 1975 the entire shelf was stable, and possibly expanding in some places, but in that year Larsen A was seen to be shrinking and thinning.

In late January 1995 (midsummer in Antarctica) a ferocious storm struck the tip of the peninsula, and a section of Larsen A broke away. The detached ICEBERG had an area of about 770 square miles (2,000 km^2) and as it moved it knocked a 656-square mile (1,700-km^2) block of ice from Larsen B. The break-up of Larsen A left Larsen B exposed. Several more icebergs broke away and in November 1998 Larsen B lost a section 395 square miles (1,024 km^2) in area. By the year 2000 Larsen B was 1,550 square miles (4,016 km^2) smaller than it had been in 1975.

The summer of 2002 was the warmest ever recorded on the peninsula. Another section of Larsen B disintegrated between January 31 and March 5, reducing the area of the ice shelf by a further 1,254 square miles (3,250 km^2).

Icebergs continue to break away from the Larsen Ice Shelf. On January 31, 2005, a section about 735 square miles (1,900 km^2) in area broke away from the southern end of the shelf.

Clearly, the Larsen Ice Shelf is disintegrating. Its loss will remove the large volume of ice at the seaward end of the GLACIERS that flow from the peninsula into the Weddell Sea, perhaps causing them to accelerate. If that happens, the part of the West Antarctic Ice Sheet covering the peninsula may grow thinner and eventually disappear.

No one knows why summer temperatures have been rising over the Antarctic Peninsula. The rise is much too rapid to be linked directly with general GLOBAL WARMING, and it began when global average temperatures were steady or falling. The rise is probably due to changes in the prevailing winds and ocean currents that carry sea pack ice across the Weddell Sea, piling it against the peninsular coast. Although the Larsen Ice Shelf has diminished greatly, this does not affect the main part of the West Antarctic Ice Sheet, and the amount of ice that has been lost is only a very small proportion of the total covering Antarctica.

last glacial maximum The time when the Wisconsinian glacial (known in Britain as the Devensian, in northern Europe as the Weichselian, and in the Alps as the Würm) reached its greatest intensity. This was the most recent GLACIAL PERIOD and its maximum happened throughout North America and Europe about 21,000 years ago.

The ICE SHEETS were then at their greatest extent, and the global mean temperature was about 9°F (5°C) cooler than that of today. Climates everywhere were generally drier. Over the ice sheets themselves, temperatures were much like those of present-day Greenland, rising above freezing for only a brief period during the summer.

(*See* APPENDIX VII: PLIOCENE, PLEISTOCENE, AND HOLOCENE GLACIALS AND INTERGLACIALS.)

late-glacial The period during which the Wisconsinian glacial (known in Britain as the Devensian, in northern Europe as the Weichselian, and in the Alps as the Würm) was drawing it to its close. This began about 14,000 years ago and continued until about 10,000 years ago, when the most recent GLACIAL PERIOD ended.

At first, late-glacial temperatures rose sharply until climates were generally warmer than those of today. This warm period is known as the Bølling INTERSTADE and it was followed by the OLDER DRYAS stade. The Older Dryas gave way to the warmer Allerød interstade, which was followed by the long, cold, YOUNGER DRYAS. The end of the Younger Dryas also marked the end of the Wisconsinian Glacial and after it temperatures rose to produce the climates of historical times.

(*See* APPENDIX VII: PLIOCENE, PLEISTOCENE, AND HOLOCENE GLACIALS AND INTERGLACIALS.)

latent heat The energy that is absorbed or released when a substance changes its phase between solid and liquid, liquid and gas, and directly between solid and gas. The absorption and release of latent heat do not alter the temperature of the substance itself, but they do alter the TEMPERATURE of the surrounding medium, because it is from that medium that absorbed latent heat is obtained and into the medium that released latent heat is introduced.

The existence of latent heat was discovered, and the term *latent heat* coined, in about 1760 by the Scottish chemist Joseph Black (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). Black called the heat latent because it cannot be measured directly with a THERMOMETER; it is hidden from the observer.

A solid consists of molecules that are tightly bound to each other by forces acting between them (*see* CHEMICAL BONDS). Energy must be supplied in the form of heat to overcome these forces. As the bonding forces weaken, groups of molecules break free, and as more heat is supplied, the solid changes into a liquid, in which small groups of molecules constantly break apart and reform and groups slide freely past each other. While this is happening, the temperature of the substance remains unchanged. All of the heat energy is used in loosening the bonds between molecules.

If still more energy is applied, it will have the effect of making the groups of molecules move faster. When they move faster, the molecules strike harder against any object with which they collide. It is the speed of motion of molecules that a thermometer measures as temperature. Once a solid has melted to become a liquid, the application of additional heat raises the temperature of the liquid.

When a liquid is cooled, its molecules lose energy, move more slowly, and the temperature of the liquid falls. When their energy falls to a certain level, the molecules start bonding together. This requires less energy than moving about, and so heat energy is released as the liquid solidifies. The temperature of the substance remains unchanged, but the surrounding medium is warmed by the release of energy.

The latent heat that is released when a liquid solidifies is exactly equal to the amount absorbed when the solid phase of the same substance melts. It is known as the latent heat of fusion or the latent heat of melting.

As the temperature of a liquid rises, its molecules move faster and faster. A point is reached at which the absorption of heat energy breaks the bonds holding groups of molecules together. Instead of raising the temperature of the liquid, this absorption of energy is used to break the bonds between molecules. Individual molecules break free and the liquid becomes a gas. When a gas is cooled, its molecules move more slowly until a point is reached at which molecules bond together into small groups and the gas condenses into a liquid. The amount of energy that is released when a gas condenses is exactly equal to the amount that is absorbed when a liquid vaporizes. It is called the latent heat of vaporization or the latent heat of condensation.

Under certain circumstances a solid will vaporize and a gas solidify without passing through the liquid phase. These processes are called SUBLIMATION and DEPOSITION, respectively, and the latent heat required for them is called the latent heat of sublimation or the latent heat of deposition.

WATER has many remarkable properties. One of them is that, because of the HYDROGEN bonds that link its molecules in its solid and liquid phases, much more latent heat is absorbed and released when it changes phase than is the case with most other substances. It is because of its high latent heat of vaporization that we are able to cool our bodies by allowing sweat to evaporate. The release of the latent heat of vaporization warms the air inside cumuliform clouds (*see* CLOUD TYPES). This causes them to continue growing upward and is a major factor in the development of storms and TROPICAL CYCLONES. The Hadley cells (*see* GENERAL CIRCULATION) are driven partly by the absorption and release of latent heat of vaporization.

The latent heat of fusion and the latent heat of melting of water at 32°F (0°C) is 80 calories per gram (334 joules per gram). The latent heat of vaporization and the latent heat of condensation is 600 cal/g (2,501 J/g) at 32°F (0°C). The latent heat of deposition and the latent heat of sublimation is equal to the sum of the latent heats of fusion and vaporization: 680 cal/g (2,835 J/g) at 32°F (0°C).

It is necessary to specify the temperature, because molecules possess an amount of internal energy that increases as the temperature of ice or water rises, and so the higher the temperature the less latent heat they need to change phase between liquid and gas. At 122°F (50°C), for example, the latent heat of vaporization is 569 cal/g (2,382 J/g) and at 194°F (90°C) it is 545 cal/g (2,283 J/g). The relationship continues at temperatures below freezing, because the lower the temperature the less energy is required for water to freeze. At -4°F (-20°C) the latent heat of fusion is 68 cal/g (289 J/g).

Laurentide ice sheet The ICE SHEET that covered Canada and the northern United States during the Wisconsinian GLACIAL PERIOD, which reached its maximum intensity about 20,000 years ago. The Laurentide ice sheet may have been joined to the GREENLAND ICE SHEET, which was then larger than it is today. The ice sheet covered southern Alaska and all of North America to the north of a line from about the positions of Seattle to Boston, passing to the south of the Great Lakes. The release of meltwater from the Laurentide ice sheet may have triggered the cold episode known as the YOUNGER DRYAS.

The line shows the boundaries of the Laurentide ice sheet at the time of the last glacial maximum, about 20,000 years ago. The sea was frozen to the north and northeast of the ice sheet.

laws of motion The three laws that were proposed by Sir Isaac Newton (1642–1727) to describe the way bodies respond to the forces acting on them.

The first law states that a body will continue in a state of rest or uniform motion unless an external force acts on it.

The second law states that the MOMENTUM of a body changes at a rate that is proportional to and in the same direction as the force acting on it. If the mass of the body remains constant, $F = ma$, where F is the force, m is the mass of the body, and a is the ACCELERATION.

The third law states that if one body exerts a force upon another body, the second body exerts an equal force in the opposite direction, called a *reaction,* upon the first body. An equation derived from the second law and known as the EQUATION OF MOTION is widely used in meteorology.

leaf area index (LAI) The ratio of the total area of plant leaves, counting one side only, to the area of ground beneath the plant. If there are 2 m^2 of leaves to every 1 m^2 of ground, for example, the LAI is 2 (the LAI is a DIMENSIONLESS NUMBER, so there are no units). In seasonal climates the LAI changes with the seasons, affecting the amount of solar energy that reaches the ground, the amount of gas exchange associated with PHOTOSYNTHESIS, and the amount of EVAPOTRANSPIRATION.

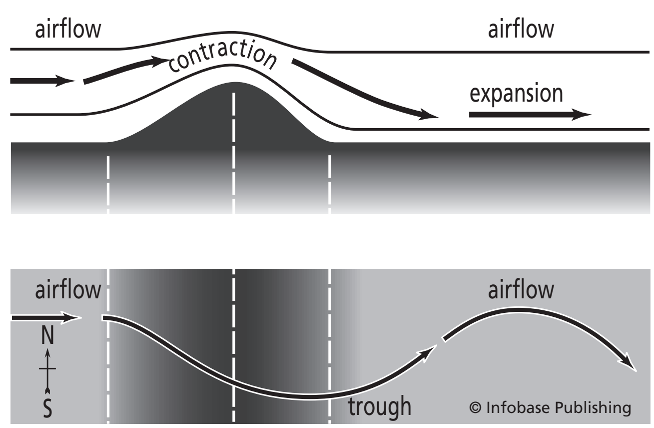
leaf margin analysis (LMA) The use of plant leaves to estimate past mean annual temperatures. The technique is based on the strong correlation that has been observed between the warmth of the climate and the likelihood that dicotyledon plants (plants with seeds that produce two seed leaves or cotyledons) will have leaves with smooth edges. The technique is possible only if the leaves that fall are preserved in sediments. If enough leaves can be recovered, they can be used in the CLIMATE-LEAF ANALYSIS MULTIVARIATE PROGRAM.

lee The adjective that describes the side of a mountain or other obstacle which is sheltered from the wind. A lee shore is the shore on the lee (sheltered) side of a ship, so the wind tends to drive a ship toward the lee shore.

A lee depression is one that forms in a westerly airflow on the lee side of a mountain range that is aligned north and south. As the air is forced to rise as it crosses the mountains, the entire atmosphere above the mountains is pushed upward and air accumulates on the upwind side of the barrier. At the same time, the layer of air immediately above the mountains is squeezed vertically, causing the layer to contract vertically, which in turn produces a lateral expansion as the air spills out to the sides. The result is a tendency for divergence (*see* STREAMLINES) and an anticyclonic (*see* ANTICYCLONE) movement of air above the mountain crest. On the other (lee) side, the descending air expands vertically once more, producing a lateral contraction to compensate. On the lee side there is, therefore, a tendency for convergence and cyclonic flow (*see* CYCLONE).

Whether divergence followed by convergence will result in the closed circulation necessary for the full development of a DEPRESSION depends upon the size of the mountain barrier. Lee depressions are common in winter to the south of the Alps and Atlas Mountains. Where they do form, lee depressions remain close to the mountains for a time, but may move away later. FRONTS may form in the depression, but this type of depression does not originate as a wave along a front. If a lee depression fails to develop there may nevertheless be a lee trough.

A lee trough, also called a dynamic trough, is a TROUGH of low pressure that forms on the lee (downwind) side of a long, meridional (north–south) mountain barrier that lies across a zonal (west–east) airflow. It is most marked to the east of the Rocky Mountains. As the air crosses the mountains, convergence on the downwind side cancels out divergence on the upwind side. This would restore the circulation pattern to its original state, except that the anticyclonic flow turned the air toward the equator (southward in the Northern Hemisphere and northward in the Southern Hemisphere) and the cyclonic flow that followed it turned the air away from the equator. Planetary VORTICITY decreases with increasing proximity to the equator. This has the effect of weakening the anticyclonic flow and strengthening the cyclonic motion in the moving air, so instead of canceling out, the air is left with a net cyclonic flow. This produces the trough. Beyond it, the circular flow carries the air northward (in the Northern Hemisphere), where planetary vorticity increases and the motion becomes anticyclonic. A series of long, horizontal waves develops, producing long-wave troughs and RIDGES.



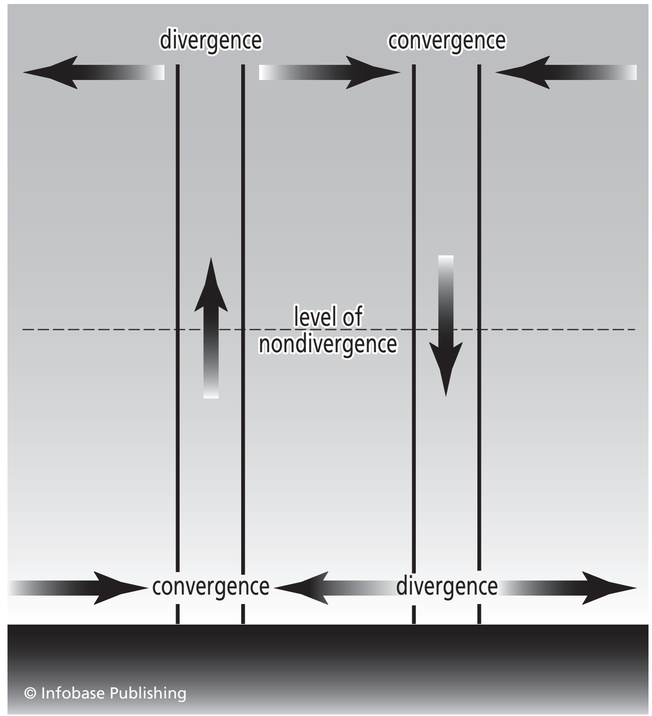
A lee trough. The upper part of the figure shows a lateral view, with air contracting as it crosses a mountain barrier and expanding on the lee side. The lower part of the figure shows the same phenomenon in plan view, illustrating the way cyclonic airflow on the lee side of the barrier forms a trough.

Waves, called lee waves or standing waves, sometimes develop in stable air (*see* STABILITY OF AIR) on the lee (downwind) side of a mountain. The mountain need not be large, but it must be steep on both the upwind and downwind side, so the air crossing it moves sharply upward and downward, and it must extend far enough across the path of the wind to prevent the air from simply flowing around it.

Air is forced to rise as it crosses the mountain. This can trigger instability if the air is conditionally unstable, but stable air returns to its former level. If there is a layer of stable air at a high level, the vertical displacement of the air will form a series of waves as air that is forced to rise sinks back to its former level. The waves remain stationary with the air moving through them. Their wavelength (*see* WAVE CHARACTERISTICS) is proportional to the wind speed, typical winds producing wavelengths of about 2–12 miles (3–20 km), and the more stable the air the shorter is the wavelength. The wavelength is not in any way related to the shape of the mountain or of other high ground that triggers the formation of the lee waves. Usually, the first wave crest is less than one wavelength downwind from the mountain peak. Wave amplitude decreases with height and with distance downwind. Wavelength increases with increasing height, and the crests and troughs are shifted progressively upwind.

Lee waves are made visible if the relative HUMIDITY is close enough to saturation for lenticular clouds (*see* CLOUD TYPES) to form at the crests. If the lee side of the mountain is very steep, a rotor, with a rotor cloud, may form beneath the crest of the first wave. A hole that forms in a layer of cloud on the LEE side of a mountain is called a wave hole. It is caused by a stream of air that descends from the mountain peak, warming adiabatically (*see* ADIABAT) as it does so and causing the EVAPORATION of CLOUD DROPLETS in its path.

level of nondivergence The height at which there is no convergence or divergence of air (*see* STREAMLINES) in a column of air that is rising or subsiding. Air that is converging at the surface is diverging at height and vice versa. Consequently, there must be a point in the column where convergence ceases and divergence begins. This is the level of nondivergence and it is usually at the height at which the air pressure is approximately 600 mb.



Nondivergence (or convergence) occurs at the level where convergence becomes divergence in a column of rising or sinking air.

lichen A composite organism that consists of a fungus and either an alga or a cyanobacterium living in close symbiotic association. Lichens are classified on the basis of their fungal component. Many lichen species are extremely sensitive to air pollution, especially by sulfur dioxide, and are widely used as pollution indicators.

light detection and ranging (LIDAR) LIDAR is a ground-based technique used to measure the density of atmospheric AEROSOLS and OZONE, as well as TEMPERATURE, in the stratosphere (*see* ATMOSPHERIC STRUCTURE). A laser beam is directed upward into the atmosphere and the desired information is calculated from an analysis of the intensity and wavelengths (*see* WAVE CHARACTERISTICS) of the light reflected back to the surface by aerosols or by atmospheric gases, depending on the lidar wavelength.

In the case of ozone measurements, the laser transmits two beams at 308 and 351 nanometers (nm). Radiation at 308 nm is absorbed by ozone, but radiation at 351 nm is not. A comparison of the intensity of light received at the surface from each beam reveals the ozone concentration.

lightning An electrical discharge that neutralizes a charge separation that has accumulated within a cloud, between two clouds, or between a cloud and the ground. Charge separation occurs within large cumulonimbus clouds (*see* CLOUD TYPES) and induces a charge on the ground surface beneath the cloud. Air is a good electrical insulator, but when the separation exceeds a critical threshold the insulation breaks down.

Atmospheric scientists are still uncertain how this happens. The breakdown potential, which is the potential gradient of the vertical electric field in the atmosphere at which dry air becomes an electrical conductor, is 3 million volts per meter. The electrical field inside clouds rarely exceeds 200,000 volts per meter. This is less than one-tenth of the breakdown potential, showing that it is necessary for local processes to build charge between cloud droplets and ice crystals and initiate a flash leader to begin the discharge. WATER conducts electricity well, and RAINDROPS and ICE CRYSTALS, which are always present in storm clouds, reduce the breakdown potential. Unfortunately, the reduction is still insufficient to account for a lightning spark.

The most likely explanation is that natural radiation from the RADIOACTIVE DECAY of naturally occurring substances and COSMIC RADIATION knock electrons (particles carrying negative electromagnetic charge) out of atoms of atmospheric gases (*see* ION). The strong electric field accelerates the electrons, which collide with air molecules freeing more electrons, and produce an avalanche of high-energy runaway electrons. The avalanche grows rapidly, turning into the lightning flash. The electric field required for this to happen is about 150,000 volts per meter, which is well within the range found inside storm clouds.

There are several stages to a lightning flash. It begins with a stepped leader, which carries negative charge away from the cloud as a stream of electrons. The stepped leader travels where the field is weakest, ionizing the air around it and producing a jagged path that is then established as the lightning channel. This is the path, about 8 inches (20 cm) across, along which a lightning stroke travels.

When it is near to the accumulated positive charge, the stepped leader triggers and is met by the much more luminous return stroke, carrying positive charge back to the cloud and traveling along the same path of ionization. The stepped leader is almost invisible. The return stroke is the main part of the flash. In the case of forked lightning, the visible flash travels not from the cloud to the ground, but from the ground to the cloud. The column of ionization that rises from a point on the ground toward which the stepped leader is descending is called a ground streamer.

The stepped leader and return stroke only partially neutralize the charge in the cloud. The first leader is neutralized by the return stroke, and the return stroke is neutralized by the charge in the cloud. This initiates a second lightning stroke, beginning from a point deeper inside the cloud and preceded by a dart leader.

The dart leader is a small lightning stroke that constitutes the third stage in a lightning flash. It carries negative charge along the lightning channel, ionizing it once more, and is met by a return stroke producing the second major flash. The process is repeated until the charge in the cloud has been fully neutralized.

Further flashes follow until the neutralization is complete. The entire process, which observers see as a single flash of lightning, usually lasts for about 0.2 second and consists of three or four flashes about 50 milliseconds apart. It is the release of energy by a lightning flash that causes THUNDER. A lightning stroke is any one of the components that together make up a flash of lightning. The stepped leader, return stroke, and dart leader are all lightning strokes.

Forked lightning is visible as brightly luminous, jagged lines between a cloud and the ground or between two clouds. It is the most dramatic form of lightning. Humans and animals directly struck by forked lightning are severely injured or killed, trees are often split apart, and lightning strikes are the cause of most naturally occurring fires. A forked lightning stroke in which the main channel has branches is known as streak lightning. It may flash between a cloud and the ground or between a cloud and adjacent air.

Sheet lightning is seen as a general flash, rather than being precisely located, as is forked lightning. Sheet lightning may be forked lightning between two clouds that is seen through an intervening cloud, or it may be a lightning flash between the separated charges inside a cloud. These discharges are thought to be less luminous and to last longer than discharges between clouds or between clouds and the ground. A cloud discharge is a flash of lightning between areas of positive and negative charge within a single cloud. To an observer on the ground a cloud discharge appears as sheet lightning.

Pearl-necklace lightning, also known as beaded lightning and chain lightning, is a rare type of lightning in which the luminosity of the discharge varies along its length, so the lightning appears as a chain of lights, or a string of pearls.

Hot lightning is lightning that ignites forest fires. The current carried by the lightning stroke is sustained for a fraction of a second until the return stroke. This generates enough heat to ignite dry material. Cold lightning does not ignite forest fires. The current carried by the lightning stroke releases heat beneath the bark of trees. This can make the sap in the tree boil, causing local explosions that strip away sections of the bark, but the current is not sustained into the return stroke.

Flaschenblitz is lightning that flashes upward from the top of a cumulonimbus cloud. At heights of about 30–55 miles (50–90 km) there are sometimes very brief events called sprites. Sprites resemble lightning and seem to be linked to cloud to ground lightning, but they can occur up to 30 miles (50 km) away from the lightning flash and up to 100 milliseconds later. Their cause is unknown.

A lightning conductor is a metal rod that projects upward from the highest point of a building or other structure and is connected to the ground by a metal strip or cable with a low resistance (less than 10 ohms). Lightning discharges, traveling by the route of least electrical resistance, are attracted to the metal, which guides them to the ground where they are earthed. A cone with an apex angle of 45° around the metal rod is protected from lightning strike. Copper is often used, because it is one of the best electrical conductors.

Benjamin Franklin (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) invented the lightning conductor and the device soon proved its worth. By 1782 about 400 had been installed in Philadelphia alone. Eventually, they were installed on ships of the British Royal Navy, where lightning often killed sailors working aloft and made holes in the hulls below the masts: Lightning destroyed 70 British naval ships in one five-year period. At first the Admiralty would permit only portable conductors to be carried. These would be hoisted to the tops of the masts when thunderstorms were likely. Not surprisingly, this resulted in even more deaths among sailors erecting lightning conductors during storms. Finally permanent conductors were allowed and ships became a great deal safer.

Linke scale (**blue-sky scale**) A set of cards that is used to measure the blueness of the sky. Each card is a different shade of blue and the cards are numbered from 2 to 26, using only the even numbers. The observer uses an odd number if the sky shade falls between those of two cards with even numbers. For example, sky shade 15 falls between shades 14 and 16, although there is no card bearing the number 15.

A cyanometer is a device for measuring the blueness of the sky. The Linke scale is the most widely used cyanometer.

liquid The phase of matter that is between the solid and gaseous phases. In a liquid, the atoms or molecules do not occupy fixed positions in relation to each other as they do in a solid, but neither are they completely disorganized, as they are in a gas. The atoms or molecules of a liquid are joined into small groups, and each group moves freely in relation to the other groups. This prevents the individual atoms or molecules from dispersing themselves evenly, so the volume of a liquid cannot increase to fill the space in which it is contained. A liquid is able to flow and will adopt the shape of the container holding it, while maintaining a constant volume.

Little Ice Age A period of cold weather that began in the 16th century and lasted until the early 20th. It affected all of the Northern Hemisphere, but only parts of the Southern Hemisphere. Its cause is uncertain, but there is evidence linking the coldest part of it to a reduction in solar output (*see* MAUNDER MINIMUM). Despite being called "the" Little Ice Age, there have been other similar fluctuations in climate, although these are not so well documented.

In the first half of the 16th century, the weather was generally mild, but there were three winters during which temperatures fell low enough for the River Thames to freeze at London. Summer temperatures at this time were very variable. Snowfall increased in central Europe during the latter part of the century, with average winter temperatures about 2.3°F (1.3°C) lower in the period 1560–99 than in 1880–1930, and in Denmark temperatures were 2.7°F (1.5°C) lower in 1582–97 than in 1982–97.

The weather began to grow warmer around 1600, but then cooled erratically to reach a minimum around the end of the 17th century. In Switzerland the mean temperature in 1687 was 7–9°F (4–5°C) lower than it is today. In 1716, the Thames froze so firmly that in January a high spring tide which raised the river level by 13 feet (4 m) simply lifted the ice together with the fair being held on it. Yet the climate was much more variable than it is now. The summers of 1718 and 1719 were so hot and dry, for example, that there was DROUGHT over much of Europe, but 1740 was the coldest year in England since records began in 1659. The temperature rose again through the 18th century, only to fall to another minimum in the early 19th.

Recovery began in the middle of the 19th century, but it was erratic. The winter of 1878–79 was as cold in England as those of the 1690s. Between 1876 and 1879 there were droughts, failures of the MONSOON, and famines in India and China. Up to 18 million people are believed to have died in the Chinese famine of the 1870s. Although the river did not freeze over, there was a considerable amount of ice on the Thames in the winter of 1894–95. It was not until the 1920s and 1930s that the weather began to grow noticeably warmer. Even then there were cold winters. In 1924, people drove cars on the sea off Lund, Sweden, and the people of Malmö could walk across the narrow sound all the way to Copenhagen.

Although the climate during the Little Ice Age was generally cooler than that of today, it was not consistently so. There were some very warm summers, and from 1840 until 1855 a shift in the ocean currents prevented the sea from freezing off Iceland. The winter of 1845–46 was unusually mild in England. The summer of 1826 was even warmer than that of 1976, which caused severe drought over much of Europe.

PRECIPITATION was also very variable. The wet years of the 1840s contributed to the outbreak of late blight of potato that destroyed most of the British crop and led to the Irish Potato Famine.

Further Reading

Lamb, H. H. *Climate, History and the Modern World.* London: Routledge, 2nd ed., 1995.

local climates Taken together, the microclimates (*see* CLIMATE CLASSIFICATION) of an area with a distinct type of surface, such as a forest, farm, or city, constitute a local climate. A local climate affects an area from 2.5 acres (1 hectare) to 39 square miles (100 km^2) up to a height of about 330 feet (100 m) above the surface. In the widely used climatological classification introduced by the Japanese climatologist M. M. Yoshino, local climates are designated L_1 to L_7.

L_1 croplands
L_2 broad-leaved forest
L_3 city
L_4 coniferous forest
L_5 and L_6 mountain environments
L_7 intermontane grassland

In addition to this technical use of the term, there are many informal names for local meteorological phenomena. A selection of these is described below, arranged alphabetically.

April showers comprise the changeable weather, with showers of rain, which occurs in the month of April in many places in middle latitudes. During winter, deep DEPRESSIONS tend to follow one another, dominating the weather pattern and bringing persistent PRECIPITATION and leaden skies. In early spring, the difference in temperature between the sea surface and land is at a maximum, with the sea much colder than the land, which is then beginning to warm up as the sunshine grows stronger. Air crossing the sea is cold, and therefore its capacity for holding moisture is low. It warms as it crosses land. This increases its capacity for holding water vapor. Water evaporates into it and condenses again in the rising air to produce cumuliform clouds (*see* CLOUD TYPES) and showers. April showers are usually light, because the air is still too cold to hold much moisture. Summer showers are much heavier. Despite its reputation, therefore, April is often drier than the summer months. In New York City, for example, an average 3.2 inches (81 mm) of rain falls in April, but 4.2 inches (107 mm) falls in July. London, England, receives an average 1.5 inches (37 mm) of rain in April, 1.8 inches (46 mm) in May, and 2.2 inches (57 mm) in July.

Bai is a yellow mist that sometimes forms in parts of China and Japan. Winds that blow during dry weather in the interior of China raise fine soil particles. These are of a loose type of silt, called loess, and are generally yellow in color. They are lifted to a great height and carried eastward where they enter moister air. Water condenses onto them and they sink as a colored mist.

Bai-u is the period of heaviest rainfall during the early part of the summer MONSOON season in Japan. It is associated with a series of shallow depressions that originate along FRONTS in central China and advance slowly across Japan in a northeasterly direction. The cloudy, humid, rainy weather they bring lasts from the middle of June until the middle of July; the name "Bai-u" means "plum rains." As the last of the depressions passes, the weather changes abruptly, becoming mainly fine, hot, and sultry. Rainfall increases again in late summer.

A buran is a type of fierce BLIZZARD that occurs in winter on the open plains of southern Russia and throughout Siberia. In northern Siberia a very similar kind of storm is called the "purga." The buran is a snowstorm driven by a wind of gale force or even hurricane force. As well as the falling snow, the air is filled with snow blown up from the ground and VISIBILITY is reduced almost to zero. The air temperature is not especially low, but the combination of WINDCHILL and disorientation due to the poor visibility make the buran very dangerous.

Calina is a HAZE that occurs in Spain and along parts of the coast of the Mediterranean Sea during the summer DROUGHT. It is caused by strong winds that pick up large amounts of DUST. The heat is intense and shimmer (*see* MIRAGE) reduces visibility still further. The calina turns the clear blue sky to a drab gray.

A chubasco is a heavy THUNDERSTORM, with strong SQUALLS, that occurs during the rainy season from May to October along the western coast of Central America, and especially in Nicaragua and Costa Rica.

Crachin is FOG, accompanied by low stratus cloud and drizzle (*see* PRECIPITATION) that is common between February and April along the coast of southern China and the Gulf of Tonkin. Sometimes it is caused by the mixing of AIR MASSES and sometimes by the ADVECTION of warm air across a cooler surface.

An elvegust, also known as a sno, is a cold, descending squall that occurs in the upper parts of Norwegian fjords.

Equinoctial rains are rainy seasons that occur in some parts of the TROPICS at around the time of the equinoxes (*see* EQUINOX).

Flaw is an old English name for a sudden squall of wind.

The friagem is a spell of cold, cloudy weather, with occasional rain, that occurs in winter in the middle and upper Amazon basin and lasts 4 or 5 days. It is caused by the incursion of polar air from beyond the southern tip of the continent, and possibly all the way from Antarctica. The polar air forms the western flank of a large air mass, and it sweeps through northern Argentina and the lowlands of eastern Bolivia into equatorial Brazil behind a cold front. The Andes prevents air behind the front from moving farther westward. With the arrival of the friagem the temperature may fall by 7°F (4°C) and it has been known to drop to 34°F (1°C) at Cuyabá, at latitude 15°S.

In North America a frog storm, also called a whippoorwill storm, is the first bad weather to occur in spring following a spell of warm weather.

Garúa, also called camanchaca or Peruvian dew, is a wet mist or very fine drizzle that falls on the lower slopes of the Andes in Peru in winter. It sometimes lasts for weeks. On the low-lying coastal fringe the mist is clear of the ground and forms a low blanket of gray stratus cloud. The garúa brings cold, dismal weather, but it also provides some moisture for vegetation in the otherwise arid climate. When Charles Darwin (1809–82) visited the region in 1835, during his voyage on HMS *Beagle,* he recorded in his *Journal* that: "A dull heavy bank of clouds constantly hung over the land, so that during the first sixteen days I had only one view of the Cordillera behind Lima. It is almost become a proverb that rain never falls in the lower part of Peru. Yet this can hardly be considered correct; for during almost every day of our visit there was a thick drizzling mist, which was sufficient to make the streets muddy and one's clothes damp; this the people are pleased to call Peruvian dew."

Gharra are severe squalls accompanied by heavy rain and thunderstorms that cross Libya from the northeast. They are frequent and appear suddenly.

The grape belt is a stretch of land that runs for about 60 miles (96 km) along the southern shore of Lake Erie. This area benefits from the LAKE EFFECT due to its proximity to Lake Erie. Winters in the grape belt are less severe than those in other parts of the United States at the same latitude, with frosts beginning late and ending early, and the fall is long and mild.

A guba is a strong squall, usually with heavy rain and thunder, which occurs at night along the southern coast of New Guinea during the summer northwest monsoon. Gubas are especially common and violent near the mouths of large valleys.

Gully squalls is a name that sailors have given to the violent squalls that blow from the mountain ravines of the Andes over the coastal waters of the eastern South Pacific.

Haar is a cold sea fog that is common along the eastern coast of Britain, especially in fine weather. The fine weather is associated with an ANTICYCLONE to the north. This draws warm air from continental Europe across the cold water of the North Sea, producing fog over a large area. The easterly winds then carry fog to the British coast. It disperses quickly as it moves inland and is warmed by contact with the sunlit ground, but it can persist all day along the coastal strip. The name may be from the Old Norse *hárr,* meaning gray (with age), and from which we also derive the word *hoary.*

The haboob is a severe dust storm (*see* DUST) that occurs in northern Sudan, most often late in the day in summer. It is associated with the northward advance of the INTERTROPICAL CONVERGENCE ZONE and develops when a strong squall blows across a surface covered with loose sand and dust. Pillars of dust rise to a height of several thousand feet and merge to form a wall of dust about 15 miles (24 km) long that advances at about 35 MPH (56 km/h). There is often thunder, but rain evaporates before reaching the ground. The storm lasts for about three hours.

A kai basakhi is a short-lived squall that occurs in Bengal at the start of the southwest monsoon. The weather then is dry and so the squall raises considerable amounts of dust.

A kona cyclone, also called a kona storm, is a persistent, slow-moving, subtropical CYCLONE that delivers most of the winter rainfall in Hawaii.

Lambing storm is the name given in parts of Britain to weather conditions that deliver a light fall of snow in the spring, which is when ewes are lambing.

Mai-u, also called plum rains, are the very heavy rains that fall during the first half of June along the valley of the Yangtze River, China. They are associated with very hot, humid air and thick, low cloud and they mark the burst of monsoon.

Maize rains are the heavy and prolonged rains that fall between February and May in East Africa.

Mango showers, also called blossom showers, are rain showers, produced by occasional thunderstorms, which fall in southern India during April and May.

Millet rains are the heavy rains that fall in East Africa between October and December, during the season when millet is sown.

A pampero is a violent squall, with winds of gale force, which blows from the southwest across the pampas of Argentina and Uruguay, north of the River Plate. The squalls form along a cold front and are accompanied by cumulus or cumulonimbus cloud, sometimes with thunderstorms, and clouds of dust. The squall usually lasts for only a few minutes, but the winds continue for several hours. The pampero is similar to the southerly burster of New South Wales, Australia, and the norther of the United States (*see* LOCAL WINDS).

The prester is a very hot, burning WHIRLWIND that appears accompanied by lightning in the Mediterranean region and especially in Greece. The same name is also applied to a WATERSPOUT accompanied by lightning.

A purga is a strong type of blizzard that occurs in winter in the tundra of northeastern Siberia. The wind blows with gale or even hurricane force and the air is filled with snow, some of it falling and some that has been swept up from the ground. Visibility is reduced almost to zero. The purga is very similar to the buran.

Rasputitsa is a rainy season in Russia that occurs in spring and autumn nearly every year and lasts for several weeks. In autumn it turns the countryside into mud, makes unpaved roads impassable, and often causes serious flooding. The autumn rasputitsa ends with the first frosts, which solidify the ground by freezing it. In spring, as the temperature rises, the frozen ground thaws and turns into mud once more. The spring rasputitsa ends as the continuing rise in temperature dries out the land.

Scotch mist is stratus cloud that forms suddenly on high ground. It is very common in Scotland and on hills and mountains in other high-latitude regions. Scotch mist is caused by adiabatic cooling (*see* ADIABAT) and CONDENSATION in very moist air that is forced to rise up the hillside, so it occurs only when there is a wind to carry air upward. It resembles a form of liquid precipitation in which mist and drizzle are mixed. All of the droplets are smaller than 0.02 inch (0.5 mm) in diameter, but they are more closely spaced than in drizzle.

Seca is the name given in northeastern Brazil to a severe drought or very dry wind. Secas are often associated with unusually warm water in the subtropical North Atlantic Ocean.

The Shūrin season is a period of high rainfall that occurs in Japan during September and early October. It is the second wet season of the year, the first being the Bai-u season during June and July. The rains of the

Shūrin season are associated with an eastward contraction of the subtropical part of the PACIFIC HIGH that allows low-pressure systems and typhoons (*see* TROPICAL CYCLONE) to move farther north. Much of the resulting rain is caused by typhoons, but some is produced by the southern sides of depressions that move along the polar front, to the north of Japan.

Silver thaw is the name given to freezing rain in the Pacific Northwest. It is called "thaw" because it is often followed by warmer weather. This is because the freezing rain is usually associated with an advancing warm front. Rain produced by the front freezes as it falls through colder air beneath the frontal slope. Air in the warm sector behind the front will soon reach places on the surface experiencing the "thaw."

Smokes are clouds of dust and dense, white, haze and mist, somewhat similar to the cacimbo, that form in the morning and evening near the western coast of equatorial Africa during the dry season. They are especially common before the onset of the harmattan (*see* LOCAL WINDS).

A sumatra is a strong squall that crosses the Malacca Strait between Malaysia and Sumatera (Sumatra) during the southwest monsoon. The squalls are generated along a front that is aligned from northwest to southeast and is sometimes more than 100 miles (60 km) long, and they advance from the southwest. Sumatras originate as sudden surges of wind that are intensified by a katabatic effect (*see* KATABATIC WIND) as they descend from the mountains. They often last for several hours and produce winds that occasionally exceed 30 MPH (48 km/h) with gusts of up to 50 MPH (80 km/h). Winds of this force are classed as 7 or 8, moderate gale or fresh gale, on the BEAUFORT WIND SCALE. Sumatras sometimes reach the Malaysian coast, but they penetrate only a short distance inland.

A terral is a land breeze (*see* LAND AND SEA BREEZES) that blows with great regularity along the western coasts of Chile and Peru. It complements the virazon. Northwesterly land breezes that occur in Brazil and in Spain, sometimes bringing squalls, are called terral levante.

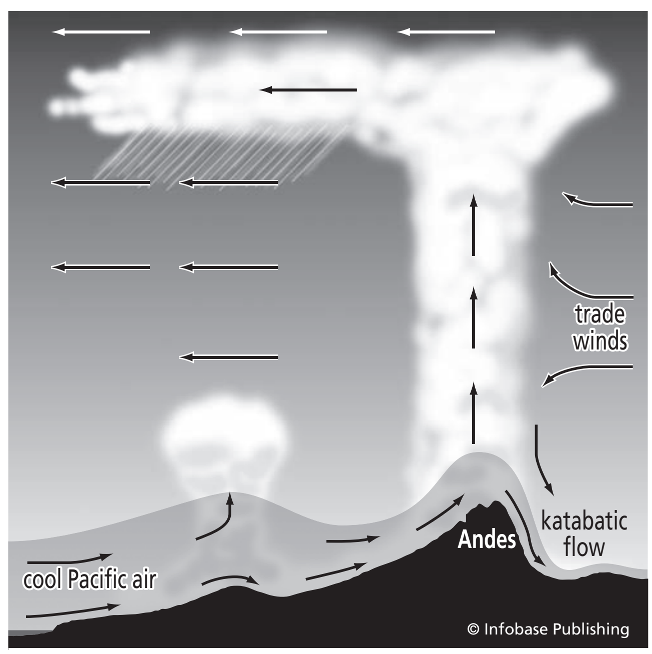
Veranillo is the name given along the western coasts of tropical Central and South America to a short dry season, a "little verano," that interrupts the long wet season. It lasts for just a few weeks and brings hot, dry weather.

Verano is the name given in parts of tropical Central and South America to the long dry season. It lasts from November until April.

A weir effect is the movement of air that is carried inland by sea breezes (*see* LAND AND SEA BREEZES) in western South America from northern Peru to central Colombia. Cool, moist air flows inland for about 37 miles (60 km), rising up the foothills of the Andes and losing some of its moisture as it does so (*see* OROGRAPHIC). Then the air rises up the main part of the range and spills over the top like water over a weir, pushed by the air behind it, and descends as a katabatic wind into the valleys that run longitudinally. The air forms a deep pool behind the mountains, and its forced rise can sometimes trigger conditional instability (*see* STABILITY OF AIR) with severe thunderstorms.

A whirly is a very small but violent storm, up to about 300 feet (100 m) across, that often occurs in Antarctica, especially around the time of the equinoxes.

A williwaw is a violent squall that occurs in the Strait of Magellan, the strip of ocean off the southernmost tip of South America that links the South Pacific



The weir effect occurs where cool air from the Pacific rises up the sides of the Andes, then spills over the top like water over a weir and descends into the north–south valleys as a katabatic wind. Orographic lifting sometimes triggers conditional instability, producing thunderstorms.

and South Atlantic Oceans. Williwaws can occur at any time of year, but they are most frequent in winter. The same name is also given to the strong squall wind that blows as cold air down deep valleys in Alaska.

A yalca is a severe squall and snowstorm that occurs in the mountain passes of Peru.

A zobaa is a whirlwind of sand, resembling a pillar, which is sometimes seen in the Egyptian desert. It is very tall and moves very rapidly.

local wind A wind that differs, in direction or strength, from the winds associated with the general distribution of pressure. The wind may be caused by a variety of factors. These include a difference in TEMPERATURE between two adjacent surfaces, producing ANTITRIPTIC WINDS such as LAKE BREEZES and LAND AND SEA BREEZES, or a KATABATIC WIND. The funneling of the wind (*see* WIND SPEED) through gaps in a mountain range produces a mountain-gap or jet-effect wind (*see* WIND SYSTEMS) with a local name. The wind affects only a small area and usually only the lowest layer of the atmosphere. Many local winds have their own names. A selection of these is described below, arranged alphabetically.

Andhis is the local name given in the northwestern part of the Indian subcontinent to a DUST storm that accompanies a violent SQUALL. The squall is caused by vigorous CONVECTION.

The austru is a cold, westerly wind that blows in winter across the low-lying plains on either side of the Danube, mainly in northern Serbia. The wind brings dry, clear air.

The autan is a wind, often strong, that blows from the southeast along the valley of the Garonne River, in southwestern France. It is a wind of the sirocco type, bringing warm, moist air and rain, although it varies in strength and in the weather associated with it. Ordinarily it is a continuation of the marin after this wind has passed through a gap in the high ground near the town of Carcassonne. If, instead, it crosses the higher ground to the southeast of Toulouse, its descent sometimes gives it the character of a FÖHN WIND. Other winds in this part of southern France are sometimes called autan, although they are not related to the true wind of that name.

The barat is a strong, westerly wind that blows on the northern coast of Sulawesi, Indonesia, during the north MONSOON. It brings squalls and sometimes causes damage. Monsoon conditions move north and south through this part of southern Asia with the movements of the equatorial trough (*see* INTERTROPICAL CONVERGENCE ZONE). The north monsoon lasts from November until April and the barat winds are most frequent between December and February.

Barinés are westerly winds that occur in eastern Venezuela. They blow from the direction of the state of Barinas.

The belat is a strong, northeasterly wind that sometimes blows across Yemen, in the south of the Arabian Peninsula. It produces hazy conditions because of the dust it carries from the desert.

A berg wind is a hot, dusty wind that blows across southern Africa, carrying continental air to the coast. Berg winds occur on the western coast on about 50 days of the year and are most frequent in winter. In southwestern Africa they are from the east, on the southern coast they are from the north, and in Natal they blow from the northwest. They last intermittently for two or three days and can bring temperatures of 90°F (32°C) or higher. They tend to die down in the late afternoon, when sea breezes neutralize them.

Bise is the name given in Switzerland to a cold, dry, fierce, northeasterly wind that blows in winter and spring through the European Alps. It is often strongest in southwestern Switzerland. A bise can whip up water from the surface of Lake Geneva and blow it over plants on the shore, encasing them in thick ice. The wind can continue for several days, and in regions affected by it many of the houses do not have doors or windows on their northeastern sides. The bise occurs when there is an ANTICYCLONE in central and eastern Europe and a DEPRESSION in the western Mediterranean. This draws continental polar (cP) air (*see* AIR MASS) through the mountains.

The bohorok is a warm, dry wind that blows during the monsoon season along the northeastern side of the mountains of Sumatra, Indonesia. It is a wind of the föhn type and the drop in relative HUMIDITY that accompanies it sometimes damages crops.

The bora is a north or northeasterly katabatic wind that blows along the coast of the Adriatic Sea. It is cold, gusty, and usually dry, although it can bring rain or snow. Its average speed is about 24 MPH (38 km/h) in summer and in winter 32 MPH (52 km/h), although in winter it can be much stronger. At Trieste it blows on an average of about 40 days a year. The bora sometimes continues for several days. Its name is from Boreas, the greek god of the north wind.

A brickfielder is a hot, dry, dust-laden, northerly wind that blows from the desert interior across southern Australia. In the north of Victoria the wind sometimes raises the temperature to above 100°F (38°C) and the hot conditions can last for several days. The name "brickfielder" originated in Sydney, where it was applied to southerly bursters that carried dust over the city from the brickfields to the south. The brickfields were where clay was dug from the ground and made into bricks. When gold mines opened in Victoria, miners were recruited from Sydney, and they gave the same name to the winds they experienced there, although these blow from the opposite direction and cross no brickfields.

A Canterbury northwester is a hot, enervating, northwesterly wind that blows across the Canterbury Plains of South Island, New Zealand. It is produced by depressions that travel from the southwest to northeast over the south of South Island or over the sea to the south. The wind brings tropical air from the interior of Australia, and it warms adiabatically (*see* ADIABAT) as it descends on the eastern side of the Southern Alps, acquiring some of the characteristics of a föhn wind.

A carcenet, also called a caracenet, is a strong, cold wind that blows through mountain gorges in the eastern Pyrenees Mountains, on the border of southwestern France and northeastern Spain. The winds are accelerated by funneling and are especially frequent in the upper part of the valley of the River Aude.

A chanduy, also called a chandui or charduy, is a cool, descending wind that blows over Guayaquil, Ecuador, during the dry season that lasts from July to November.

The chergui is a hot, dry wind that blows from the east across Morocco, in North Africa. Because it has crossed a long stretch of DESERT, the wind has a strongly drying effect.

The chili is a hot, dry wind that blows from the south over Tunisia, in North Africa, most commonly in spring. It is a wind of the sirocco type.

The chinook is a warm, dry, katabatic wind that blows mainly in late winter and spring on the eastern side of the Rocky Mountains in Canada and the United States. It is of the same type as the föhn wind of the European Alps. The chinook occurs when there is a strong flow of air across the mountains. A TROUGH of low pressure forms on the eastern (lee) side of the mountains, and this pulls air down the mountainsides. A cloud known as the chinook wall cloud forms over the mountains and is a reliable indicator of an approaching chinook. The air has lost its moisture on the western (windward) side of the mountains, so it descends as dry air and warms at the dry adiabatic LAPSE RATE of 5.4°F per 1,000 feet (9.8°C per km). When it reaches the plains to the east of the mountains, the subsiding air produces a large and rapid rise in temperature. The temperature sometimes rises by about 40°F (22°C) in less than five minutes. The wind can reach speeds of 100 MPH (160 km/h) and because the air it brings is so dry it can sublimate (*see* SUBLIMATION) large amounts of snow—often up to 6 inches (15 cm) a day. The relative humidity during a chinook usually falls to below 50 percent and has been known to reach 10 percent. This gives the wind its alternative name of "snow eater." The name "chinook" is taken from the Native American people of that name, whose lands are in the northwest of North America.

The colla, also called the colla tempestade, is a southerly or southwesterly moderate gale (*see* BEAUFORT WIND SCALE), blowing at up to 39 MPH (63 km/h), with heavy rain and severe squalls, that occurs over the Philippines.

The collada is a moderate gale that blows from the north or northwest over the northern part of the Gulf of California and from the northeast over the southern part.

Contrastes are winds that blow along the shore, but from opposite directions on the two sides of a headland. They occur in winter along the Mediterranean coast of Europe.

The criador is a westerly wind that brings rain in northern Spain.

The crivetz is a northeasterly wind that blows in spring and autumn through the lands bordering the lower Danube in Romania and southern Ukraine. It brings hot weather in late spring and early autumn and cold weather, sometimes with snow, during the colder months.

The dadur is a northwesterly wind that blows from the Siwalik Hills, in the foothills of the Himalayas, down the valley of the Ganga River, in India.

The düsenwind is a strong northeasterly wind that blows through the Dardanelles, which is the strait in Turkey that links the Sea of Marmara with the Aegean

Sea. It blows when there is an area of high atmospheric pressure over the Black Sea and lower pressure over the Aegean.

The embata is an onshore wind from the southwest that blows across the Canary Islands. It is caused by a reversal of the trade winds (*see* WIND SYSTEMS) in the LEE of the islands.

Etesian winds are dry winds that blow from the north over the eastern Mediterranean. They are most frequent from May to October and commonly attain speeds of 40 MPH (64 km/h) but can be so strong it is impossible for sailing vessels to travel against them. In Turkey, where they are called *meltemi,* they blow from the northwest and often bring relief from the intense summer heat. The winds are associated with low-pressure systems and are very dependable. The name "etesian" is from the Greek *etesiai,* meaning "annual."

The furiani is a strong southwesterly wind that blows in the region near the Po River, Italy. It lasts for only a short time and is followed by a southerly or southeasterly gale.

The gallego is a cold, northerly wind that blows across Spain and Portugal.

The gending is a dry, southerly föhn wind that blows across the northern plains of Java. The wind crosses the mountains near the south coast of the island and is funneled between the volcanoes.

The gharbi is a wind that blows across the Mediterranean from the Sahara to the Adriatic and Aegean Seas. It sometimes reaches gale force, but it consists of warm air that has crossed the sea and it brings damp, oppressive weather. The gharbi often produces fog, heavy DEW, and heavy rain, especially on mountainous coasts. The rain is sometimes red because of the desert dust it carries.

The ghibli is a hot, dry wind of the sirocco type that blows in northern Libya. It occurs when a depression moves along the Mediterranean, drawing air from far to the south into the cyclonic flow (*see* CYCLONE).

A gregale is a strong, northeasterly wind that blows across Malta and the adjacent parts of the Mediterranean region. It is associated with a large anticyclone over the Balkans and a cyclone over North Africa. Its name means "wind from Greece" in the Maltese language. The gregale most often occurs in spring and fall. It brings very variable weather, sometimes with clear skies and at other times with mist and heavy rain. It also causes high seas to run into harbors, endangering ships.

The harmattan is a moderate or strong, hot, dry, dusty wind that blows across West Africa to the south of the Sahara, from the north on the eastern side of the desert and from the northeast on the western side. It occurs at all times of year, but only during the day; at night the wind dies down. It is the trade wind, and it becomes hotter and drier as it crosses the desert, and it is usually trapped beneath a temperature INVERSION that prevents the air from rising by convection. The harmattan is so dry that it hardens leather, warps wood, and in some places reduces the average relative humidity to below 25 percent. In the TROPICS, however, it brings welcome relief from the high humidity and is sometimes called the doctor.

The helm wind is a cold, northeasterly wind that blows along the valley of the River Eden in Cumbria, northwestern England, especially during late winter and spring. It derives its name from the distinctive cloud, shaped like a helmet (or helm), that is seen when the wind is blowing over the high ground of the western side of the Crossfell Range. The cloud itself is known as a helm bar and comprises a thick bank of cloud along the top of the hills, with a narrow band of almost motionless cloud protruding from it away from the hills.

The jauk is a föhn wind that occurs in the Klagenfurt Basin, Austria.

Junk wind is the name that is given in Thailand, Vietnam, China, and Japan to the southerly or southeasterly monsoon wind. The name refers to the fact that this wind is favorable to the sailors of junks (traditional flat-bottomed sailing ships).

The junta is a mountain-gap wind that blows through passes in the Andes. It sometimes reaches hurricane force.

The juran, also called the joran, is a cold northwesterly wind that blows through the Jura Mountains, near Geneva, Switzerland. The juran often produces snow and is sometimes very blustery.

The kachchan is a hot, dry, westerly or southwesterly föhn wind that blows from the mountains of central Sri Lanka in June and July, during the southwest monsoon. It is especially strong at Batticaloa, on the eastern coast directly to the northeast of the mountains. There the kachchan wind is often powerful enough to overcome the afternoon sea breeze and bring temperatures approaching 100°F (38°C).

The karaburan is a hot, dry wind of up to gale force that blows from the east-northeast across the deserts of Central Asia from early spring to the end of summer. Its name means "black storm" because of the large amount of desert dust it carries, darkening the sky. It is caused by the rapid heating of the Central Asian landmass.

The karema is a strong easterly wind that blows across Lake Tanganyika, in East Africa.

The karif, also spelled kharif, is a strong, southwesterly wind, often reaching gale force, which blows across the coast of Somalia on the southern side of the Gulf of Aden during the southwest monsoon. The wind is fiercely hot and heavily laden with sand.

The kaus, also called the cowshee or sharki, is a southeasterly wind that blows over the Persian Gulf ahead of a depression. It can reach gale force and is usually associated with cloudy weather and squalls. After the depression has passed the kaus may be followed by another type of wind known as a suhaili.

The khamsin is a hot, dry wind that blows from the southeast across Egypt and the Sudan. Its name is the Arabic word for "fifty" and refers to the fact that the wind usually blows on 50 days of every year in late winter and early spring. It is a wind of the sirocco type associated with a low-pressure system over the Sudan that extends to the northeast, while at the same time a shallow depression is situated over the northern Sahara. These combine to draw in air from Arabia and possibly from as far away as the Arabian Sea. The khamsin air is hot, with temperatures often exceeding 100°F (38°C), extremely dry, and the wind carries so much fine dust that visibility is seriously reduced and cars must use their headlights in the middle of the day. The wind lasts for two or three days.

A kloof wind is a cold, southwesterly wind that blows across Simons Bay, South Africa.

A knik wind is a strong, southeasterly wind that blows in the area around Palmer, Alaska. It can occur at any time of year, but is most frequent in winter.

The koembang is a dry, warm, southerly or southeasterly wind of the föhn type that blows in Java, Indonesia. The wind is caused by the monsoon and is accelerated by funneling as it passes through gaps in the mountains before descending on the lee side of the mountains, in the area around Tegal, on the northern side of the island.

The kona is a southwesterly wind that blows across Hawaii about five times a year. It brings storms and heavy rain to the southwestern slopes of the mountains, which are ordinarily on the lee side of the northeasterly trade winds.

The leste is a hot, dry, easterly or southeasterly wind which blows from Africa to Madeira and the Canary Islands, lying off the northwestern coast of Africa. The wind brings much dust from the desert. Like the sirocco, it occurs ahead of a depression that is moving toward the east.

The levanter, also called the solano, levante, or llevante, is a strong easterly wind, sometimes of gale force, that blows across southern Spain and the Strait of Gibraltar. It brings air from the lands along the eastern coast of the Mediterranean, a region that was formerly known as the Levant, hence the name. The wind occurs at all times of year and brings moist weather, often with fog, that lasts for several days. It is caused by low-pressure systems.

The levantera is a persistent easterly wind that blows over the Adriatic Sea, and that usually brings cloudy weather.

The leveche is a hot, dry wind of the sirocco type that blows from the south over southeastern Spain bringing air from the Sahara. It is produced by depressions traveling eastward along the Mediterranean.

The libeccio is a southwesterly wind that blows across Corsica and Italy at any time of year, but especially in winter when it may bring storms.

The llebatjado is a hot, gusty wind that blows down from the Pyrenees across Catalonia, in northern Spain.

The llevantades is a levanter wind that brings especially stormy weather.

The maestrale is a cold, northerly or northwesterly wind that blows over northern Italy, most commonly near Genoa, and land bordering the Adriatic Sea. It is similar to the mistral and its name means "masterful."

The maestro is a northwesterly wind that blows across Italy and over the Adriatic Sea, and also onto the western shores of Sardinia and Corsica. It brings fine weather and is most common in summer.

The marin is a southeasterly wind of the sirocco type that is common in the land bordering the Gulf of Lions, in southern France. It blows ahead of depressions, sometimes reaching gale force. Usually it brings warm, cloudy weather and heavy rain. Because it is an onshore wind it can cause danger to ships. There is a gap in the high ground near the town of Carcassonne. After the marin has passed through this gap it becomes the autan.

The mistral is a cold, northerly wind that blows over southern Europe bordering the Mediterranean, but especially along the lower part of the Rhône River valley to the Gulf of Lions, France. It can occur at any time of year but is most frequent in winter and spring. Its name means "masterful" and it has been known to blow trains over. As a means of protection, many houses in the Rhône Valley have no windows or doors in their north-facing walls. The mistral can reach more than 80 MPH (130 km/h) and produce freezing temperatures. It is caused by a flow of polar air driven by a large anticyclone to the north, sometimes far to the north, or the AZORES HIGH, and a depression centered south of Toulon.

The moazagotl is a föhn-type wind associated with a LEE WAVE cloud that occurs in Silesia.

The n'aschi is a northeasterly wind that blows in winter along the Iranian coast, bordering the Persian Gulf, and on the coast of Pakistan, bordering the Arabian Sea.

The nevados is a cold, katabatic wind that blows down the mountainsides and into the high valleys of Ecuador. It is caused by radiative cooling at night, which chills the surface air. The cold air starts to flow downhill gravitationally and is chilled further by contact with the snow- and ice-covered surface across which it moves.

A nor'easter, also called a northeast storm, is a storm that produces northeasterly winds of up to hurricane force in eastern North America from Virginia to the Canadian Maritime Provinces. A nor'easter develops when a deep depression forms over the North Atlantic, off Cape Hatteras, North Carolina, and then moves northward. As the depression travels along the coast, the cyclonic circulation around the center of low pressure draws maritime polar air over the area to the east of the Appalachians. Nor'easters are most common between September and April and as well as the fierce winds they bring freezing or near-freezing temperatures and heavy falls of snow.

The norte, also called the papagayo, is a cold, northerly wind that blows in winter down the eastern coast of Mexico. It can reduce temperatures to below freezing and cause frosts at elevations above 4,000 feet (1,220 m). It is a southern continuation of a norther.

A norther is a cold, strong, winter wind that blows from the north across the southeastern United States, sometimes extending across the Gulf of Mexico and Central America into the Pacific. Northers are caused by COLD WAVES originating in the northwest that bring polar air southward. Near the Gulf, where the weather is ordinarily warm, the sudden chill as a norther arrives is dramatic. The temperature falls to well below freezing. At San Antonio, Texas, the January mean temperature is 53°F (12°C), and it has been known to exceed 80°F (27°C), but during a norther it has fallen to 4°F (-15°C). At Houston, the temperature on one night was 75°F (24°C) at midnight. Then a norther arrived and at 9 A.M. the temperature was 22°F (-5°C). Sleet or snow may fall, but more commonly the sky remains clear. A norther wind continues to blow for a day or more.

A north föhn is a föhn wind that is generated by a movement of air from north to south across the Alps.

A nor'wester, also called a northwester, is a wind or weather system that arrives from the northwest. In South Island, New Zealand, a nor'wester is a hot, dry wind that blows from the mountains. In northern India, nor'westers are storms which are caused by convection when dry, potentially cold air (*see* POTENTIAL TEMPERATURE) overruns warm, humid air. These conditions are especially common in the Ganga Delta in the weeks before the break of the summer monsoon. In South Africa, a nor'wester is a depression associated with an active front between maritime tropical air and maritime polar air that brings storms, rain, overcast skies, variable winds, and cold weather to southwestern coasts in winter.

The oberwind is a mountain breeze that blows at night in the Salzkammergut region of Austria.

The ouari is a southerly wind, similar to the khamsin, which blows across Somalia, Africa.

The panas oetara is a strong, warm, dry, northerly wind that blows in Indonesia in February.

The polacke is a cold, dry, katabatic wind that blows in winter over northern Bohemia, in the Czech Republic. It descends from the Sudeten (Polish Sudety) Mountains, bringing air from Poland.

The ponente is a westerly wind that blows along the Mediterranean coast of France and in Corsica.

The poniente is a westerly wind that blows through the Straits of Gibraltar.

The poriaz, also called the poriza, is a strong, northeasterly wind that blows across the Black Sea in the region of the Bosporus, which is the strait that links the Black Sea with the Sea of Marmara and forms part of the boundary between Europe and Asia.

The puelche, also called the fog wind, is a föhn wind that occurs on the western side of the Andes. It sometimes brings violent squalls.

The raffiche is a mountain wind that blows in gusts in the Mediterranean region.

The reshabar is a strong, dry, northeasterly, katabatic wind that blows down the sides of the mountain ranges in Kurdistan, in southern Iraq and Iran. The name means "black wind." The reshabar is hot in summer and cold in winter.

The samoon is a hot, dry, northwesterly föhn wind that blows from Kurdistan across Iran.

The Santa Ana is a wind of the föhn type that occurs in southern California, most commonly in autumn and winter. It forms part of the clockwise movement of air around a strong anticyclone centered over the Great Basin. This brings air from the desert of Arizona and Nevada toward the Pacific. As the wind crosses the Coastal Range funneling intensifies it. Funneling is especially marked through the Santa Ana Canyon, which gives the wind its name. Then, as it descends on the western side of the mountains, the air warms adiabatically (*see* ADIABAT). The wind is dry, carries a large amount of dust, and often blows at 40 MPH (64 km/h) with gusts of twice that speed. Its temperature is often close to 90°F (32°C) and sometimes higher. It has a strongly desiccating effect on vegetation and will fan and drive fires.

The scharnitzer is a cold, persistent, northerly wind that blows through the Tyrol, Austria.

Sea turn is a name that is given in the northeastern United States, and especially in New England, to a wind that blows from the sea and often brings mist.

The seistan is a wind that blows almost incessantly between June and September from the north or northwest in eastern Iran and western Afghanistan, but mainly in the Iranian border region of Seistan. This is a depression covering an area of about 7,000 square miles (18,130 km^2) centered on latitude 30.5°N, longitude 61°E. The seistan wind is caused by the monsoon and is also known as the "wind of 120 days." It can attain speeds of 80 MPH (129 km/h). The seistan is hot, extremely dry, and carries large amounts of dust and salt.

The selatan is a strong, dry wind that blows from the south over parts of Indonesia during the southeast monsoon.

The shamal is a hot, dry wind that blows almost continuously during June and July over Iraq, Iran, and the Arabian Peninsula. It is associated with the flow of air around an area of low pressure centered over Pakistan. The wind seldom exceeds 30 MPH (50 km/h) but the shamal brings large dust storms.

The siffanto is a southwesterly wind that blows over the Adriatic Sea and surrounding lands. It is often violent.

The sigua is a gale that blows in the Philippines. It is associated with the monsoon.

The simoom is a hot, dry wind of the sirocco type that blows in spring and summer across the southeastern Sahara and the Arabian Peninsula. It often carries large amounts of dust and sand. The simoom occurs when a depression moves along the Mediterranean and air from far to the south is drawn into the cyclonic flow.

The sirocco is a hot wind that blows across countries bordering the Mediterranean, most commonly in spring. It occurs ahead of depressions that move from west to east along the Mediterranean, the wind occurring first in the west and then progressively farther to the east, Israel and Lebanon experiencing it four or five days after Algeria. The cyclonic flow of air around the center of low pressure draws air from far to the south, so by the time it approaches the North African coast the air has traveled across a long stretch of desert and it reaches the coast as a hot, dry, dusty wind. The air may then cross the Mediterranean, cooling and acquiring moisture as it does so, to reach southern Europe as a warm, moist wind that can cause fog, heavy dew, and rain—sometimes BLOOD RAIN. As the depression continues to move to the east, the airflow changes and the sirocco disappears, to give way to cold mistral or bora winds from the north.

Solaire is the name given to an easterly wind in central and southern France, referring to the fact that easterly winds blow from the direction of the rising Sun (in French, *soleil*).

A southerly burster is a strong, cold wind that blows from the south across the eastern part of New South Wales, Australia. It is generated by a trough of low pressure lying between two anticyclones that are moving in an easterly direction. Sometimes the trough extends almost to the north of Australia. The trough, shaped like an inverted V, is an extension of a depression centered over the Southern Ocean. As it passes, the hot air that is drawn down from the north by the anticyclones is replaced by polar air.

A sudestada is a strong southeasterly wind that blows in winter along the Atlantic coasts of Argentina, Uruguay, and southern Brazil. Sudestadas bring heavy rain and fog as well as stormy seas. They are caused by primary cyclones, many with long troughs extending from them, that cross South America from west to east below about latitude 40°S, moving at up to 30 MPH (50 km/h) in summer and 40 MPH (64 km/h) in winter. The sudestadas are the Southern Hemisphere counterparts of the Northern Hemisphere nor'easters.

The suhaili is a strong southwesterly wind that blows across the Persian Gulf in the wake of a depression. It often follows a kaus wind. The suhaili brings thick cloud, rain, and sometimes fog.

The sukhovei is a hot, dry, easterly wind that blows across southern Russia and the European steppe. It occurs most often in summer and it can damage crops and bring drought.

The surazo is a cold, dry, southerly or southwesterly wind that blows across the mountain ranges and high plateau of Peru, often with great force. It brings clear skies and temperatures below freezing.

The tarantata is a strong northwesterly breeze that blows in the Mediterranean region.

The tehuantepecer is a cold, northerly wind that blows almost constantly in winter over the isthmus of Tehuantepec, Mexico. It brings heavy rain to the northern coast, but is dry by the time it reaches the Pacific. The tehantepecer is a southerly extension of the norther and norte.

The temporale is a strong southwesterly or westerly wind that blows onto the Pacific coast of Central America during the summer. It brings hot, humid air and weather similar to that of the Asian monsoon. The wind is caused by the deflection of the southeasterly trade winds in the eastern South Pacific Ocean.

The tongara is a hazy southeasterly wind that blows through the Makasar Strait, Indonesia.

The touriello is a southerly wind of the föhn type that descends from the Pyrenees and blows along the Ariège valley, in southwestern France. The wind is especially violent in February and March, when it sometimes melts the snow, causing flooding and avalanches.

The tramontana is a northerly or northeasterly wind that blows in the northwestern part of the Mediterranean region, bringing cool, polar air.

The vardarac, also called the vardar, is a cold, northwesterly wind resembling the mistral that blows in the fall along the valley of the Vardar River, in Macedonia, from Skopje to the Aegean Sea.

The vaudaire, also called the vauderon, is a strong, southerly, föhn wind that blows across Lake Geneva, Switzerland.

The vendaval is a strong, sometimes gale-force, southwesterly wind that blows along the coast of Spain, bringing heavy rain and high seas. In the Strait of Gibraltar and along the coast to its east, the vendaval is usually from between the southwest and northwest.

The vent du Midi is a southerly wind that blows through the central region of the Massif Central and Cevennes in southern France, bringing warm, moist air. The name means "wind of the Midi" (the Midi is the south of France).

The virazon is a southwesterly sea breeze (*see* LAND AND SEA BREEZES) that blows onto the western coasts of Chile and Peru, where the Andes Mountains descend steeply toward the sea. It occurs with great regularity, commencing at about 10 A.M. and reaching its greatest force at about 3 P.M. In summer the virazon is often so strong that boats are unable to put to sea. A westerly sea breeze affecting the Atlantic coasts of Spain and Portugal is also called virazon.

The wasatch is a strong, easterly, jet-effect wind (*see* WIND SYSTEMS) that blows across the plains of Utah from the mouths of canyons in the Wasatch Mountains.

The yamase is a cool, onshore, easterly wind that blows in the Senriku district of Japan.

The zonda is a warm, dry wind of the chinook and föhn type that occurs in winter in the lee of the Andes in Argentina. In dry weather it carries a great deal of dust and it can attain speeds of 75 MPH (120 km/h).

low An area in which the AIR PRESSURE is lower than the air pressure in the surrounding area. The term refers only to horizontal comparisons of pressure and not to differences in pressure at varying heights through a column of air, and the term most commonly refers to the situation at sea level. Comparisons can be made at any height above the surface, however, provided the pressures being compared are measured at the same height. Thus it would be correct to speak of a low at a particular height, although this use of the term is unusual.

The term also refers only to measurements taken at the same time and not to variations in pressure in the same place but at different times.

Air circulates cyclonically around a low and "low" is often used interchangeably with CYCLONE, but the two words are not synonymous (*see also* HIGH).

A region of low air pressure within which there is more than one low-pressure center is known as a complex low.

An area of low air pressure produced by the warming of air that is in contact with a warm surface is known as a thermal low, also called a heat low. Intense surface heating causes thermal lows. The warm air expands and becomes less dense and the expansion extends throughout much of the column of air above the warm surface. Thermal lows occur in the Persian Gulf, Spain, northern India, and in the southwestern United States, all of which are regions dominated by SUBTROPICAL HIGHS.

Thermal lows draw in air that is sometimes moist and produces rain. For example, every summer a thermal low develops over southwestern Arizona. As a result of the moist air flowing into the low, Phoenix receives an average of 1 inch (25 mm) of rain in both July and August, when the average daytime temperatures are 104°F (40°C) and 101°F (38°C), respectively, compared with 0.1 inch (2.5 mm) in both May and June, when the average temperatures are 91°F (33°C) and 101°F (38°C), respectively.

M

Madden-Julian Oscillation (**MJO**) An atmospheric disturbance that was first described in 1972 by Roland A. Madden and Paul R. Julian. It begins over the Indian Ocean and travels eastward as a wave with a 30–60 day period. An MJO causes a warming in the lower atmosphere, and several MJO cycles can amplify the effect. The MJO is now recognized as the principal fluctuation lasting less than one year affecting variations in tropical weather.

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magnetic declination The difference in the direction of the north and south magnetic poles and the north and south true or geographic poles. This difference occurs because the magnetic poles are not located at the geographic poles. The magnetic North Pole is located in the islands of northern Canada, at approximately 77.3°N 101.8°W, and the magnetic South Pole is at approximately 65.8°S 139.0°E. The declination varies from place to place and from time to time, because the magnetic poles slowly change their location. In Seattle, for example, the declination is about 21° east, but in central Wisconsin it is only 2° east and in Door County, Wisconsin, it is about 3.5° west.

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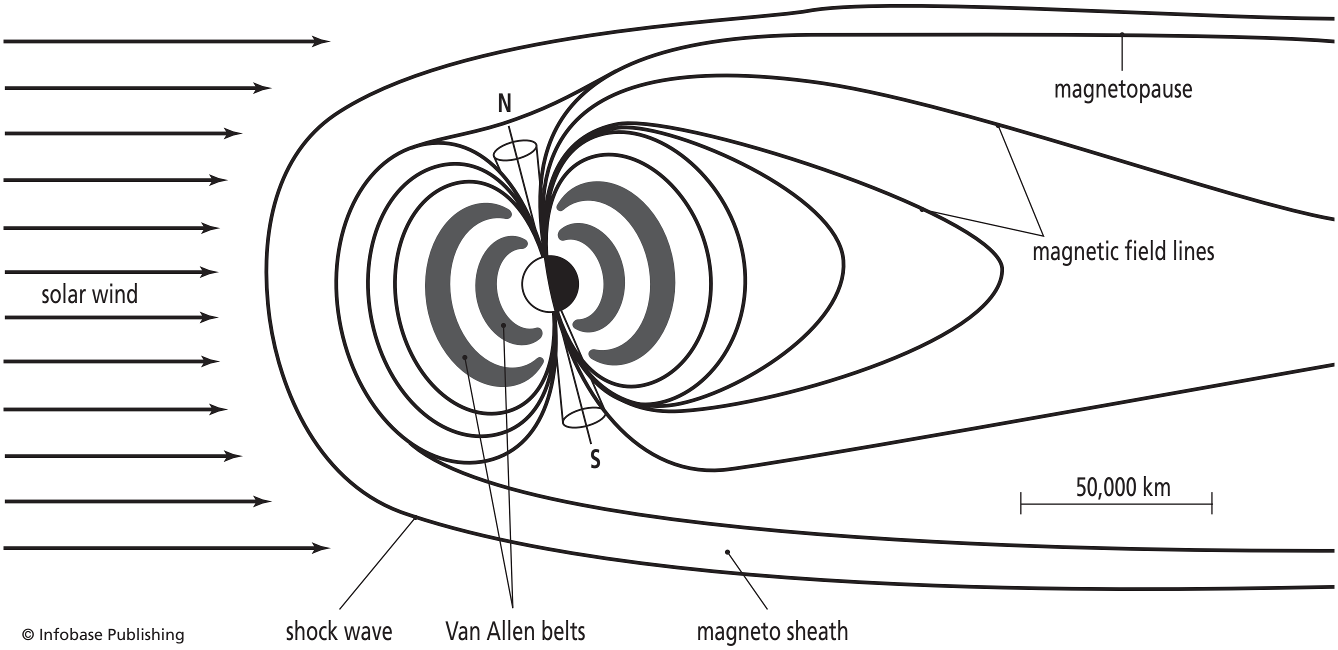
magnetosphere The region of space that lies above the exosphere (*see* ATMOSPHERIC STRUCTURE). It consists of a PLASMA that is constantly maintained by bombardment by the SOLAR WIND. The charged particles of the magnetospheric plasma are concentrated in the two Van Allen radiation belts.

The Van Allen radiation belts are two toroidal (doughnut-shaped) regions of the magnetosphere that were discovered in 1958 by the American physicist James Albert Van Allen (1914–2006). The belts consist of charged particles, trapped from the solar wind and belonging to the plasma that makes up the magnetosphere. The centers of the belts are about 1,865 miles (3,000 km) and 9,940 miles (16,000 km) above the Earth's surface.

Gravity has a negligible effect on particles within the magnetosphere, but electromagnetic forces affect them strongly, and their movement is often oriented in the direction of the magnetic field. There is a bow shock wave, called the magnetopause, at a distance of 10–15 Earth radii, where the solar wind and magnetosphere interact and the solar wind particles are deflected. The magnetopause is a boundary current carrying charged particles. When a plasma such as the solar



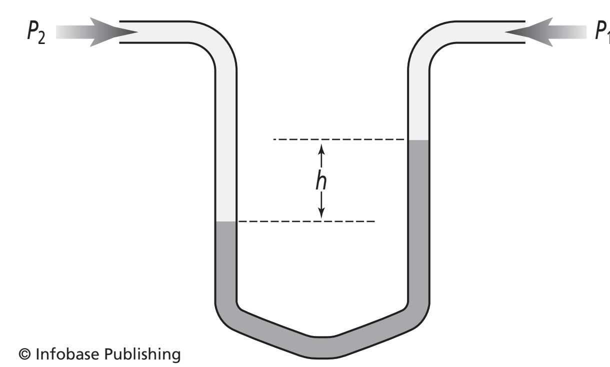
The impact of the solar wind causes a bow shock wave on the side of the magnetosphere facing the Sun. On the opposite side, the magnetosphere is stretched into a long magnetotail. The charged particles are concentrated in the two Van Allen radiation belts.

wind flows across a magnetic field, its particles are deflected in a direction perpendicular to their original velocity and to the local magnetic field. It is this reaction that generates the boundary current.

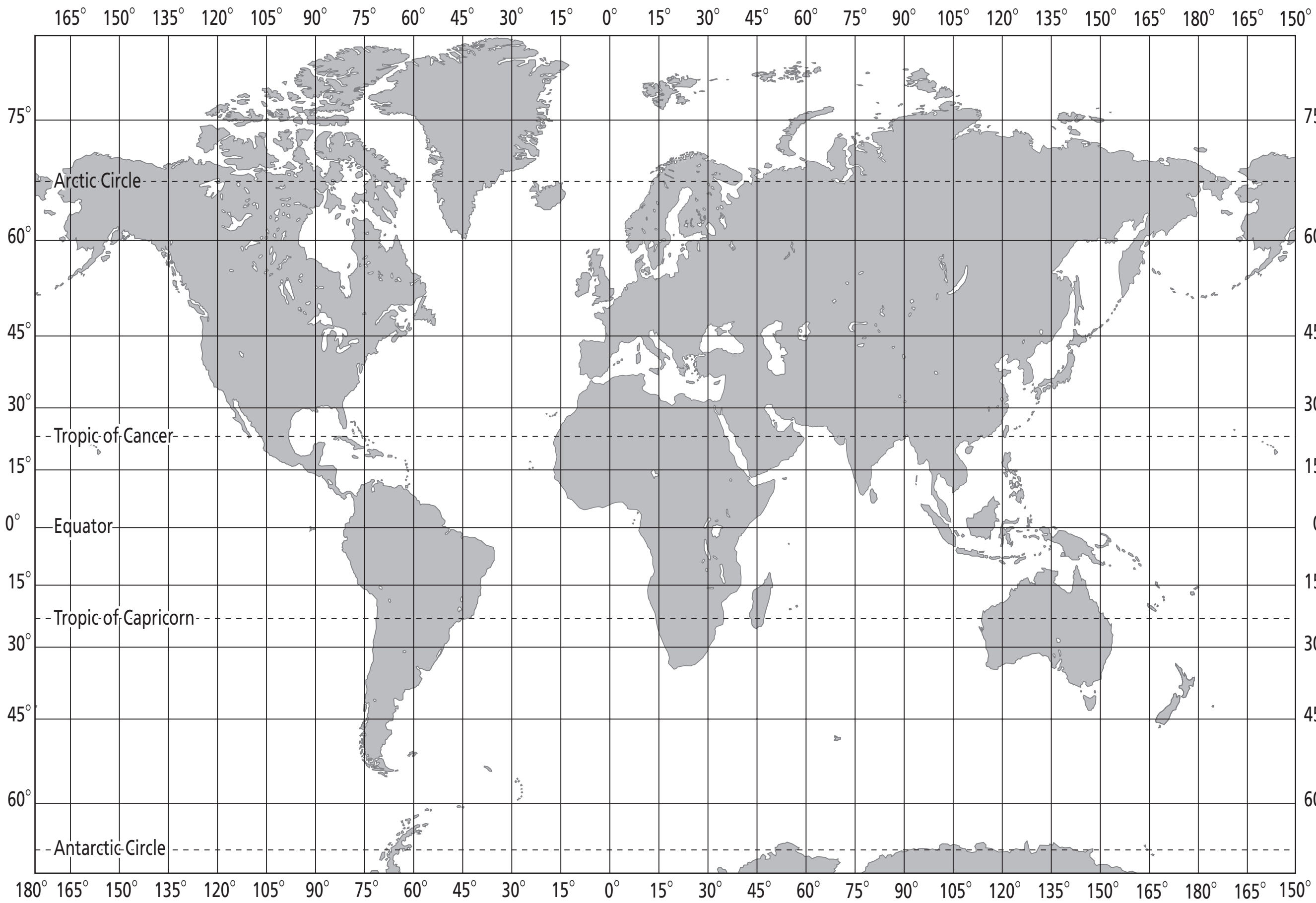
On the side facing the Sun, the magnetosphere extends to a distance of 8–13 Earth radii. On the opposite side of the Earth, the magnetosphere is stretched into a "magnetotail" that extends for a distance of 200 to more than 500 Earth radii and that is 50–60 Earth radii in diameter. Although the density of particles in the magnetosphere is extremely low, the total volume of the magnetosphere is between 100,000 and 1,000,000 times greater than that of Earth itself. (One Earth radius is 3,959 miles, 6,371 km.)

The magnetosheath is a region of the magnetosphere that lies between the bow shock wave and the magnetopause. It is where some solar wind particles penetrate the shock wave. A small proportion of magnetosheath particles penetrates the magnetopause, producing a boundary layer beneath it.

manometer (**differential manometer**) An instrument that is used to measure the difference between the pressures exerted by two fluids. The simplest manometer consists of a glass tube bent into a U shape and containing a liquid that is much denser than either of the fluids being measured. When the two ends of the tube are connected to the fluids being measured, the fluid exerting the greater pressure pushes the liquid through the tube, so its surface is higher on one side of the U than it is on the other side. The difference in pressure can then be calculated from the difference between the



A manometer measures the difference in pressure exerted by two fluids. The liquid level will be lower in the side of the tube connected to the source of greater pressure.



A cylindrical map projection

two heights, using the equation: $p_1 - p_2 = \rho g h$, where p_1 and p_2 are the pressures of the two fluids being compared, ρ is the density of the liquid, g is the gravitational acceleration (32.18 feet per second per second; 9.807 m s^{-2}), and h is the difference in height of the two liquid columns.

If one end of the tube is open to the atmosphere, the position of the liquid will show the difference between the pressure exerted by one fluid and atmospheric pressure. A BAROMETER is a manometer in which one of the pressures is made equal to zero ($p_2 = 0$).

map projection The Earth is approximately spherical in shape, but for convenience maps are drawn on flat surfaces. Consequently, a means must be devised to represent a curved surface in two dimensions without distorting it to a degree that would make the map misleading or difficult to use. In other words, the features of the Earth's curved surface must be projected onto a flat surface. The result is a map projection, and there are several ways to achieve a projection that is acceptable. The equal-area and cylindrical projections are the most widely used, Mercator's projection being the most familiar of the cylindrical projections.

In an equal-angle projection all the angles between lines on the map are equal to the corresponding angles on the surface of the spherical Earth. The equal-angle projection represents all the angles correctly, but areas, and therefore distances, are distorted.

In an equal-area projection, the map is imagined to be at right angles to the plane of the equator. The equator appears as a straight, horizontal line and one meridian as a straight, vertical line at right angles to the equator. All other lines of latitude and longitude appear as arcs of circles, those of latitude (known as small circles) decreasing in size with distance from the equator.

Equal-area projections often confine the Earth within an ellipse in order to minimize the distortions of shapes.

The Mercator projection is the method by which some of the most familiar maps are produced. It bears the name of the Flemish geographer Gerardus Mercator (the Latinized name of Gerhard Kremer, 1512–94). Mercator did not invent the projection, but in 1569 he used it to produce a map of the world, and he was the first person to apply it to a nautical chart.

Mercator used a cylindrical projection, as though a cylinder was wrapped around the globe, surface features projected onto the inside of the cylinder, and then the cylinder was unrolled as a flat sheet. In this projection, lines of latitude and longitude appear as straight lines intersecting at right angles, just as they do on the spherical globe. Its great advantage is that a navigator can represent the desired track between two points as a straight line that intersects all the lines of latitude and longitude at the same angle. This is called a rhumb line, and its use simplifies navigation, even though it is not the shortest distance. The shortest distance between two points on the surface of a sphere is a great circle, which is the shorter arc of a circle passing through the two points, the center of which coincides with the center of the sphere. A great circle appears as an arc on a Mercator projection and is difficult to draw accurately. The disadvantage of the Mercator projection is that it does not represent all areas to the same scale, and the shapes of some areas are distorted.

Mars atmosphere Compared with that of Earth, the atmosphere of the planet Mars is cold and thin. The surface atmospheric pressure is about 6 mb (on Earth it is 1013.2 mb). The composition of the atmosphere by volume is: CARBON DIOXIDE 95.3 percent; NITROGEN 2.7 percent; ARGON 1.6 percent; and OXYGEN 0.13 percent. There are traces of water vapor; CARBON MONOXIDE; NEON; KRYPTON; and XENON.

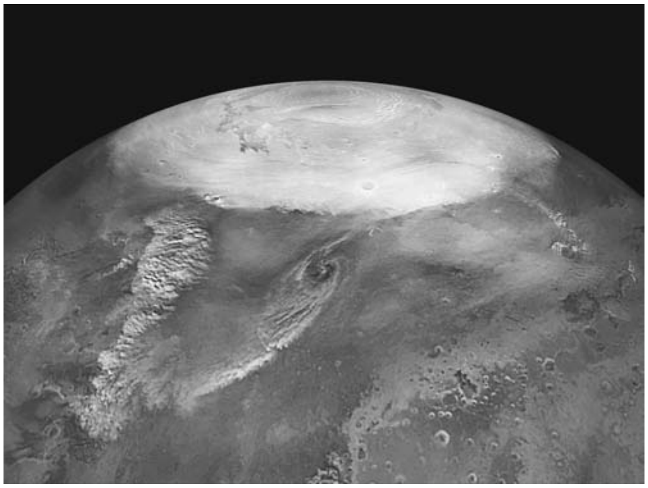
Mars is about half the size of Earth. Its average diameter is 4,212 miles (6,779 km). The average diameter of Earth is 7,918 miles (12,740 km). Mars is also farther than Earth from the Sun. Mars is 1.52 astronomical units (AU) from the Sun, 1 AU being the average distance between Earth and the Sun, so Mars is 1.52 times more distant from the Sun than Earth. The average distance between Mars and the Sun is 141,642,000 miles (227,940,000 km) and between Earth and the Sun it is 92,961,000 miles (149,600,000 km).

The global mean surface temperature on Mars is -67.27°F (218 K, -55.15°C), but this ranges from a minimum of -208°F (140 K, -133°C) to a maximum of 80°F (300 K, 27°C) in dark regions of the tropics in summer. The atmospheric pressure is too low for water to exist on the surface as a liquid. Consequently, water changes directly between the solid and gaseous phases (*see* DEPOSITION and SUBLIMATION). Scientists believe there are large reservoirs of water in the form of ice at the poles and below ground elsewhere. There may also be a reservoir of carbon dioxide in the form of limestone and other carbonate rocks.

There is a permanent ice cap made from solid carbon dioxide at the Martian south pole and an ice cap of water ice at the north pole. Both polar caps expand and retreat with the seasons, as carbon dioxide and water vapor are added to and removed from each in turn.

Martian air is very dusty. The smallest particles, 0.1 µm to 1 µm in size, are especially abundant and they scatter light (*see* SCATTERING) just as DUST particles do on Earth, but on Mars the effect is to make the sky pink at all times of day. The dust particles are thrown into the air by the impact of bigger sand grains, about 100 µm across, that bounce along the surface

The surface of Mars photographed by the Viking 2 Lander on September 5, 1976. This scene is in Utopia Planitia and it is seen in the afternoon looking toward the northeast, with the Sun behind the camera. The large rock to the left of center is about 3 feet (1 m) wide. The horizon appears tilted because the lander is at an angle of 8°. ***(NASA)***



Spring dust storms near the north polar ice cap of Mars. Martian dust storms result from the sharp difference in temperature between the layer of solid carbon dioxide forming a frost cap and the warm ground adjacent to it. These storms were photographed in May 2002 by the Mars Orbiter Camera carried on the Mars Global Surveyor, and the picture is a mosaic of images. The north polar cap is the bright, frosty area at the top of the picture. ***(NASA/JPL/Malin Space Science Systems)***

(the process is called saltation) driven by the constant wind. Dust storms are common and have a significant climatic effect by altering the ALBEDO at the polar ice caps and shading the surface from sunlight.

In addition to many local dust storms, there are major dust storms that occur every year. Mars has an orbit of high ECCENTRICITY (0.093), and the planet is at PERIHELION during the southern hemisphere summer. The dust storms commence in the southern hemisphere spring, as the surface warms and the ice cap retreats. The sublimation of carbon dioxide and water vapor absorbs LATENT HEAT from the ground beneath the ice, chilling it just as sunshine is warming the adjacent surface. This produces large temperature differences locally, causing strong CONVECTION that raises dust. As the southern summer progresses, the dust storms spread, eventually to envelop the entire planet.

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Maunder minimum The period from 1645 to 1715 when very few SUNSPOTS were observed. The period was identified by the English astronomer Edward Walter Maunder (1851–1928; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) by searching through old records. Maunder found a period of 32 years during which not a single sunspot was recorded in the Sun's Northern Hemisphere and several periods of 10 years during which no sunspots were reported anywhere on the Sun. Fewer sunspots were seen over the entire 70 years than are seen today in an average single year.

This was not the only period of sunspot absence. The German astronomer Friedrich Wilhelm Gustav Spörer (1822–95) had already alerted Maunder to a similar period, now known as the SPÖRER MINIMUM. Maunder published several papers on his discovery, but these attracted little attention. Scientists knew that the number of sunspots increased and decreased over an 11-year cycle and interpreted this as meaning that the Sun behaved in a very regular fashion. Maunder contradicted this idea by showing that in the recent past solar behavior had departed dramatically from the regular cycle, and he was ignored.

There is no doubt that the Maunder minimum really occurred. Sunspots had always interested astronomers, who recorded them meticulously, and by the middle of the 17th century they used excellent telescopes. Several of the most eminent scientists commented on the absence of sunspots. The number of sunspots also affects the frequency of auroras, or northern lights (*see* OPTICAL PHENOMENA), which can be seen without instruments. These were also much rarer during the Maunder minimum than they are now. In Scandinavia, where they are seen almost every night, they were so uncommon that people regarded them as omens. When one was seen in England in 1716, at the end of the minimum, Edmund Halley, the Astronomer Royal, wrote a paper explaining it, in which he said it was the first he had ever seen.

Final confirmation of the Maunder minimum came through measurements of the proportion of carbon-14 present in wood dated to the period (*see* RADIOCARBON DATING). Carbon-14 is formed in the atmosphere by collisions between cosmic rays and nitrogen atoms and the intensity of COSMIC RADIATION is affected by the strength of the Sun's magnetic field. When there are few sunspots, the solar field is weak and more cosmic radiation enters the atmosphere, increasing the formation of carbon-14. Carbon-14 formation increased during the Maunder minimum.

Both the Spörer and Maunder minima correspond precisely with periods of unusually low average temperatures. These occurred during the LITTLE ICE AGE and mark its coldest episodes. During the minima average temperatures in Europe were 1.8°F (1°C) lower than they are today and Alpine glaciers advanced. Conditions were much warmer from about 1510 to 1645, between the two minima.

Since the Spörer and Maunder minima were recognized other, similar episodes have been identified, and also sunspot maxima, when there were more sunspots than usual. In each case, a major change in the number of sunspots coincides with a period of warmer or cooler climate. There was a warm period during the Middle Ages, for example, that began around 600 C.E. and reached its peak between 1100 and 1300. Such changes are now known to have occurred at intervals over the last 5,000 years.

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mean (**average**) The average value of a set of values. The terms *mean* and *average* are synonymous, but most scientists and mathematicians prefer *mean,* because *average* also connotes "ordinary," "standard," or "generally prevailing."

The arithmetic mean, which is the mean that is most often meant by the word *mean,* is calculated by adding together all the values and dividing their sum by the number of values:

$$X_a = \Sigma x/n$$

where X_a is the arithmetic mean, Σx is the sum of all the variables, and n is the number of variables. The geometric mean (X_g) is given by the nth root of the sum of the variables:

$$X_g = \sqrt[n]{\Sigma x}$$

The daily mean is the mean value of a meteorological factor over 24 hours counted from midnight to midnight. It is obtained by adding together the hourly readings for TEMPERATURE, pressure, cloud cover, or the amount of PRECIPITATION that has fallen in the preceding hour, and dividing the total by 24. In the case of temperature and pressure, the mean can be calculated by adding the highest and lowest values recorded and dividing by two. The extent to which the value of a meteorological factor differs from the mean value is called its departure.

mean free path The average distance that a molecule travels before colliding with another molecule. It is proportional to the DENSITY of the medium through which the molecule travels and is also related to its VISCOSITY.

The free path, which is the actual distance a particular molecule travels between two collisions, cannot be known, because to calculate it would require knowledge of the position and motion of all other molecules in the vicinity. Consequently, the mean free path is calculated as a probability. In air at sea-level pressure and 32°F (0°C) the mean free path of an OXYGEN molecule is 2×10^{-6} inch (6 μm).

medieval warm period A time when the global climate was warmer than it had been in the preceding centuries and warmer than it was in the following centuries. Temperatures began to rise in about 800 C.E., and as early as 600 C.E. in Greenland, and the peak occurred between 1100 C.E. and 1300 C.E., after which temperatures fell as the world entered the LITTLE ICE AGE. During the medieval warm period the TREE LINE in central Europe was up to 650 feet (198 m) higher than it was in the 17th century.

The early part of the warm period was the time when Viking ships sailed the northern seas and when Norsemen established colonies in Iceland and Greenland (in the 980s). In about 1000 C.E. Viking sailors whose ships had been blown off course accidentally discovered the North American coast. They called it Vinland, or Wine-land, but difficulties with local people prevented them from colonizing it. By that time surface temperatures in Norwegian fjords were probably about 7°F (4°C) warmer than they are now.

During the peak of the period, settled farms were established in northern Norway and expanded onto higher ground elsewhere in Europe. The period also coincided with the building of cathedrals in Europe and with the Crusades, both of which may have been facilitated by the warmer conditions and resulting abundance of food.

Summer temperatures during the warm period were probably about 1.3–1.8°F (0.7–1.0°C) warmer than the 20th century average in England and 1.8–2.5°F (1.0–1.4°C) warmer in central Europe. The warm period passed its peak in Greenland during the 12th century, and conditions began to deteriorate in Europe from the early 14th century.

As temperatures fell, the medieval warm period gave way to the LITTLE ICE AGE. The Little Ice Age was generally cold, but temperatures recovered for several decades during the middle to late 16th century. This brief episode of warm weather is known as the little medieval warm period.

meridional flow The movement of air that flows in a north–south or south–north direction, parallel to the meridians (lines of longitude), on a smaller scale than that of the meridional circulation (*see* GENERAL CIRCULATION). Meridional flow occurs when waves develop in the midlatitude westerlies (*see* WIND SYSTEMS). Its effect is to carry warm air into higher latitudes than it reaches at other times and to carry cool air closer to the equator.

The component of air movement that is parallel to the lines of longitude (meridians) is called the meridional index. It is averaged along the whole of a line of latitude and takes no account of the direction of the meridional flow (north or south).

meridional overturning circulation (MOC) An alternative name for the GREAT CONVEYOR, which takes account of forces other than the THERMOHALINE CIRCULATION that are involved in this system of ocean currents. In particular, MOC (pronounced "mock") recognizes that surface currents are driven by the WIND. Consequently, even if the thermohaline circulation were to shut down completely, the surface GYRES, such as the Gulf Stream (*see* APPENDIX VI: OCEAN CURRENTS) would continue to flow as they do today.

Further Reading

Kerr, Richard A. "Confronting the Bogeyman of the Climate System." *Science,* 310, 432–433, October 21, 2005.

Mesoarchean The era of the Earth's history that lasted from 3,200–2,800 million years ago, during the ARCHEAN eon. The Earth's atmosphere contained little oxygen during the Mesoarchean, although stromatolites existed at that time. Stromatolites are the fossil remains of laminated mounds formed from successive mats of cyanobacteria (or possibly other bacteria). Cyanobacteria perform PHOTOSYNTHESIS, so they were releasing oxygen into the air as a photosynthetic by-product. *See* APPENDIX V: GEOLOGIC TIMESCALE.

mesocyclone A mass of air that spirals upward at the center of a very large cumulonimbus storm cloud (*see* CLOUD TYPES) that has developed a SUPERCELL. WIND SHEAR deflects air that is rising convectively through the cloud. This causes the rising air to start rotating cyclonically about its own vertical axis, starting high in the cloud, where the upcurrent starts to level off as it enters the anvil. Rotation then spreads downward until the entire system of upcurrents is turning, with the diameter of the VORTEX decreasing progressively as it descends lower.

Reducing the diameter of the vortex accelerates the angular VELOCITY of air in the vortex in order to conserve the angular MOMENTUM. If the vortex extends through the base of the cloud, it becomes a funnel cloud, and if the funnel cloud reaches the ground, it becomes a TORNADO.

mesophyte A plant that is adapted to conditions that are neither extremely wet nor extremely dry.

Mesoproterozoic The middle era of the PROTEROZOIC eon, which lasted from 1,600–1,000 million years ago. The Mesoproterozoic is divided into three periods: the Calymmian (1,600–1,400 million years ago); Ectasian (1,400–1,200 million years ago); and Stenian (1,200–1,000 million years ago).

Rodinia, the first known supercontinent, formed during the Mesoproterozoic, and another supercontinent, Pannotia, may have appeared during the Stenian period at the very end of the Mesoproterozoic. Stromatolites, the mounds formed by layers of cyanobacteria or other bacteria that first appeared during the MESOARCHEAN, flourished and OXYGEN had started to accumulate in the atmosphere, which contained approximately 1 percent of the present O_2 concentration.

Single-celled organisms may have begun to join together into multicellular forms during this time, and some organisms may have begun to reproduce sexually. The first fungi appeared on land. *See* APPENDIX V: GEOLOGIC TIMESCALE.

Mesozoic The era of Earth's history that began 251 million years ago and ended 65.5 million years ago. The Mesozoic is divided into three periods: the Triassic (251–199.6 million years ago); Jurassic (199.6–145.5 million years ago; and Cretaceous (145.5–65.5 million years ago).

During the Mesozoic the supercontinent Pangea broke into two smaller continents: Laurasia in the north and Gondwana in the south. Mesozoic climates throughout the world were as warm as present-day tropical climates. During the Triassic climates were generally dry and highly seasonal, with a large temperature range in the interior of Pangea, where there were vast DESERTS. Deserts began to diminish in size during the Jurassic, and with the break-up of Pangea seasonal temperature differences became less extreme. Climates also became wetter. This trend toward more moderate temperatures and higher rainfall continued through the Cretaceous, until there was very little difference in temperature between the equator and the poles. Climates probably began to grow cooler toward the end of the Cretaceous, but this is uncertain.

Many modern forms of plants and animals appeared for the first time during the Mesozoic. This is when the first flowering plants appeared. Marine reptiles swam in the seas, pterosaurs flew in the air, and dinosaurs walked on land. The Mesozoic ended with the extinction of many animal groups in what is known to paleontologists as the Cretaceous–Tertiary boundary event (K/T event). Most scientists agree that this extinction resulted from a collision between Earth and an asteroid. *See* APPENDIX V: GEOLOGIC TIMESCALE.

Meteor 3 A Russian satellite, launched on August 15, 1991, that carrying a Total Ozone Mapping Spectrometer (*see* SATELLITE INSTRUMENTS) that is used to measure the emission and subsequent spread of sulfur dioxide from volcanoes. In early 2006, *Meteor 3* was still in orbit and transmitting data.

Meteorological Office The British government agency that gathers meteorological data and compiles and issues weather forecasts. It was formed in 1854 as a small department within the Board of Trade. Commanded by Admiral Robert FitzRoy (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), its task was to provide information on the weather and sea currents for the use of mariners. It began issuing storm warnings to seaports and weather forecasts to the press in 1861. These services were suspended in 1866, on the advice of a committee of the Royal Society, but were reinstated in 1879.

During the First World War meteorological services were established in all branches of the military, and in 1920 these were brought together under the control of the Air Ministry. Naval meteorological services were taken over by the Admiralty in 1937. In April 1990, the Meteorological Office became an Executive Agency of the Ministry of Defence, and in April 1, 1996, it was made a Trading Fund, allowing it to enter into commercial contracts with its customers. The Hadley Centre for Climate Prediction and Research was opened in May 1990 as part of the Meteorological Office.

The Meteorological Office Web site home page is at www.metoffice.gov.uk/.

meteorology The scientific study of the atmospheric phenomena that produce weather, and especially the application of this study to the forecasting of weather (*see* WEATHER FORECASTING). The word is derived from the Greek word *meteorologia,* which in turn is derived from *meteoron,* which means "of the atmosphere" and *meteoros,* which means "lofty."

People have always been fascinated by the weather, and predicting it has always been important. Farmers planning to sow a crop needed to know whether their seedlings would survive, fishermen needed to know whether a storm was developing, and ordinary people needed to know whether they should take a coat when they left home. It is not surprising, therefore, that meteorology originated a very long time ago, in ancient Greece. The first book on the subject was written by Aristotle in about 340 B.C.E. It was called *Meteorologica,* and it gave us the name of the science.

Archimedes discovered that when a body is immersed in a fluid it displaces its own volume of that fluid. This is known as Archimedes' principle, and meteorologists apply it when they calculate the BUOYANCY of a rising PARCEL OF AIR.

Since then, many of the greatest scientists have contributed to the study. Galileo invented a THERMOMETER, and his associate Torricelli invented the BAROMETER. Robert Boyle, Edmé Mariotte, Jacques

Charles, and Joseph Gay-Lussac discovered the relationship between the temperature and pressure of a gas and from that came the GAS LAWS. Blaise Pascal proved that atmospheric pressure decreases with height. The astronomer Edmund Halley was the first person to propose an explanation for the trade winds (*see* WIND SYSTEMS), which led George Hadley and, much later, William Ferrel to complete the explanation of the GENERAL CIRCULATION of the atmosphere. Thomas Jefferson was one of many enthusiasts who kept detailed weather records. Benjamin Franklin demonstrated the electrical nature of THUNDERSTORMS. The German-born English astronomer Sir William Herschel (1738–1822) discovered invisible infrared radiation (*see* SOLAR SPECTRUM). That made it possible to study the heat balance of the atmosphere and the GREENHOUSE EFFECT, outlined by John Tyndall and Svante Arrhenius.

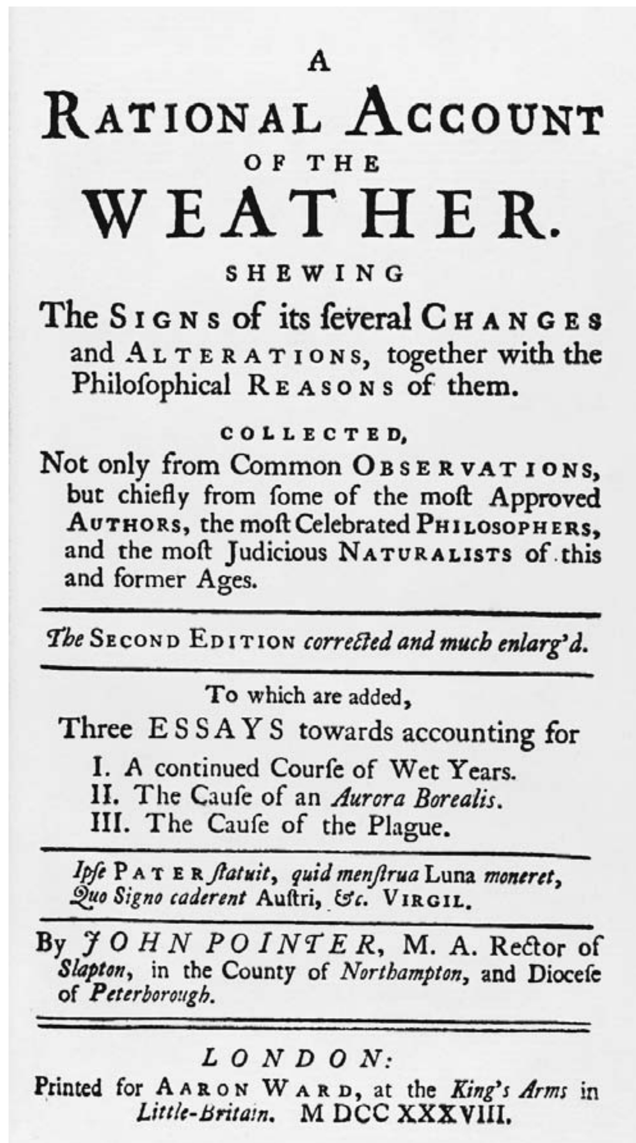
Many scholars attempted to classify clouds. The classification used today is based on one devised in the 19th century by Luke Howard.

The invention of reliable instruments made it possible to measure TEMPERATURE, AIR PRESSURE, HUMIDITY, and WIND SPEED and direction, but it was still possible to study the weather only on a local scale and weather forecasting had to rely on local observations. It was not possible to examine conditions simultaneously over a large area in time to compile a forecast, because no information could travel faster than the speed of a horse. That changed in the middle of the 19th century with the introduction of TELEGRAPHY, invented by Joseph Henry and Samuel Morse, and the MORSE CODE to translate the letters of the alphabet and numerals into sets of "on" and "off" signals.

Lewis Richardson devised a way to forecast the weather mathematically. The mathematics that he used are those that apply to quantities that are constantly changing. This branch of mathematics is called the calculus, and it was invented independently by the English physicist and mathematician Sir Isaac Newton (1642–1727) and the German mathematician Gottfried Wilhelm Leibniz (1646–1716). Richardson's method was too complex to be used in his own lifetime, but his ideas strongly influence modern forecasting techniques. These rely on satellite images and measurements as well as observations from surface stations and modern meteorologists have at their disposal large, powerful supercomputers to perform the hundreds of thousands of mathematical calculations that are required to produce a forecast.

(*See* APPENDIX I: BIOGRAPHICAL ENTRIES for information about Aristotle, Arrhenius, Boyle, Charles, Ferrel, Franklin, Galileo, Gay-Lussac, Hadley, Halley, Henry, Howard, Mariotte, Morse, Pascal, Richardson, Torricelli, and Tyndall.)

Like all major scientific disciplines, meteorology comprises a number of specialized branches.



A

RATIONAL ACCOUNT

OF THE

WEATHER.

SHEWING

The SIGNS of its ſeveral CHANGES and ALTERATIONS, together with the Philoſophical REASONS of them.

COLLECTED,

Not only from Common OBSERVATIONS, but chiefly from ſome of the moſt Approved AUTHORS, the moſt Celebrated PHILOSOPHERS, and the moſt Judicious NATURALISTS of this and former Ages.

The SECOND EDITION *corrected and much enlarg'd.*

To which are added,

Three ESSAYS towards accounting for

I. A continued Courſe of Wet Years.

II. The Cauſe of an *Aurora Borealis*.

III. The Cauſe of the Plague.

Ipſe PATER *ſtatuit, quid menſtrua* Luna *moneret,*
Quo Signo caderent Auſtri, *&c.* VIRGIL.

By *JOHN POINTER*, M. A. Rector of *Slapton*, in the County of *Northampton*, and Dioceſe of *Peterborough*.

LONDON:

Printed for AARON WARD, at the *King's Arms* in *Little-Britain*. M DCC XXXVIII.

Title page of *A Rational Account of the Weather* by John Pointer (1668–1754), published in 1738. ***(Steve Nicklas, Treasures of the NOAA Library Collection)***

Aerology is the scientific study of the free atmosphere (*see* PLANETARY BOUNDARY LAYER) throughout its vertical extent, with particular reference to the chemical and physical reactions that occur at particular levels within it. Aerology forms one part of meteorology, and the two words are sometimes used synonymously, but unlike meteorology, aerology is not confined to studies of the lower atmosphere where meteorological phenomena occur.

Mountain meteorology is the study of the effects that mountains have on the atmosphere and the weather conditions these produce.

Macrometeorology is the scientific study of the atmosphere at the largest scale, including the general circulation and the development and behavior of AIR MASSES and large weather systems.

Mesometeorology is the study of weather systems that extend horizontally for about 0.6–60 miles (1–100 km). Satellite images make it possible for meteorology to be conducted at this scale. These show the clouds associated with such phenomena as frontal systems (*see* FRONT), SQUALL lines, and TROPICAL CYCLONES as well as showing large individual cumulonimbus clouds (*see* CLOUD TYPES) associated with THUNDERSTORMS and the GUST fronts they produce. Through its widespread use of satellite images, modern weather forecasting relies heavily on mesometeorology.

Micrometeorology is the scientific study of the atmospheric conditions that prevail inside a microclimate (*see* CLIMATE CLASSIFICATION). It includes the study of phenomena that are very important locally, such as the behavior of air as it crosses a particular area of high ground, convective movements and cloud formation that result from uneven heating of the ground, and the TURBULENT FLOW that is produced by particular surfaces (*see* AERODYNAMIC ROUGHNESS).

Synoptic meteorology is the study of weather conditions over a large area simultaneously (that is, synoptically).

Descriptive meteorology, also called aerography, is the branch of meteorology in which the composition and structure of the atmosphere and atmospheric phenomena are described, using verbal accounts, graphs, tables, and other illustrations. It does not include any discussion of the causes of these phenomena or of meteorological theory.

Physical meteorology is concerned with the physical processes involved in producing the day-to-day weather. These include such phenomena as EVAPORATION and CONDENSATION and the formation of clouds and fog, the mechanisms by which CLOUD DROPLETS grow and cause PRECIPITATION, the separation of electrical charge that leads to thunderstorms, and the development of SUPERCELLS, MESOCYCLONES, and TORNADOES.

Radar meteorology involves the use of RADAR in compiling a picture of the present state of the weather and in preparing weather forecasts. WEATHER RADAR reveals details of the size and type of clouds, location and intensity of precipitation, and the direction and speed of movement of weather systems. Thunderstorms, tornadoes, and tropical cyclones also produce clear and distinctive radar images.

Dynamic meteorology is the scientific study of atmospheric motion that predicts the future state of the atmosphere in terms of the physical variables of temperature, pressure, and VELOCITY. The laws of fluid mechanics and thermodynamics are expressed in the form of complex mathematical equations (partial differential equations).

Hydrometeorology specializes in the study of precipitation. Types of precipitation are sometimes called "hydrometeors." This is the aspect of meteorology that is of most direct concern to farmers and growers, irrigation engineers, flood-control engineers, designers and managers of hydroelectric schemes, and others with a particular interest in surface waters.

Biometeorology is the scientific study of the relationship between living organisms and the air around them. This includes the effect that organisms have on the air, through PHOTOSYNTHESIS, RESPIRATION, and TRANSPIRATION, as well as the emission of gases and particulate material by plants (*see* ISOPRENE) and animals, and as a consequence of human activity (*see* AIR POLLUTION and GREENHOUSE EFFECT). Plants also affect the atmosphere by shading the ground beneath them and by intercepting precipitation. This produces distinct microclimates in shaded and unshaded areas. The study also includes the response of plants and animals to atmospheric conditions. Plants wilt during a DROUGHT, for example, and many animals seek shade when the sky is clear and the sunshine intense. Biometeorology also includes specialized subdisciplines, such as agrometeorology.

Agrometeorology is the study of weather systems in terms of their effects on farming and horticulture and the provision of meteorological services for farmers and growers. Agricultural and horticultural weather forecasts provide information on the likely effect of forthcoming weather on particular crops.

Forensic meteorology is concerned with the relevance of atmospheric conditions to legal problems. A forensic meteorologist might be asked to comment on such matters as whether a particular flood should have been anticipated in the design of the building it damaged, or whether the reduced VISIBILITY that caused an accident was due to natural FOG or industrial pollution. The issue may relate to an insurance claim or to the possibility of individual or corporate liability. Forensic meteorologists are consulted on LIGHTNING strikes, tornado and tropical cyclone damage, ICE STORMS, as well on damage or injury that might have resulted from air pollution. Several universities now offer postgraduate courses in forensic meteorology, and many companies have been established to offer forensic meteorological services.

Anemology is the scientific study of winds. The word is derived from the Greek *anemos,* which means "wind," and *logos,* which means "word."

Applied meteorology is the preparation of weather reports and forecasts for specified groups of users, such as farmers, fishermen, and aircraft pilots. Specialized reports and forecasts are also prepared for climbers, backpackers, skiers, and others planning outdoor activities.

Industrial meteorology is the study of the ways in which day-to-day weather conditions affect a particular industry.

Marine meteorology specializes in the study of weather conditions over the open ocean, coastal seas, coastal land areas, and islands. Marine meteorologists prepare reports and forecasts primarily for the use of ships and aircraft.

Naval meteorology is concerned with weather conditions over the oceans and the interactions between the oceans and atmosphere.

Meteosat A series of European meteorological satellites in geostationary ORBITS, the first of which was launched by the United States in 1977. Meteosat satellites are now launched by the European Space Agency. At present there are 8 Meteosat satellites in orbit.

The second Meteosat generation, Meteosat Second Generation (MSG), will comprise three satellites in GEOSTATIONARY ORBITS. MSG started to replace the first generation Meteosat program in 2003, and the process will be completed in 2012. The first, *MSG-1,* was launched in October 2000 by an Ariane launcher. *MSG-2* was launched on an Ariane rocket in December 2005 into an orbit above the Gulf of Guinea. *MSG-2* also carries a Geostationary Earth Radiation Budget instrument (*see* SATELLITE INSTRUMENTS).

(Further information about MSG is available from www.esa.int/SPECIALS/MSG/.)

methane (CH_4) A greenhouse gas with a global warming potential (GWP) of about 21 (*see* GREENHOUSE EFFECT) that is present in the atmosphere at a concentration of about 1.745 parts per million by volume. There is slightly more methane in the atmosphere over the Northern Hemisphere than there is in the Southern Hemisphere atmosphere. Methane is the second most important greenhouse gas after CARBON DIOXIDE (not counting water vapor) because although its GWP is fairly low it is much more abundant than other greenhouse gases.

Methane enters the air as a by-product of digestive processes in ruminant mammals (cattle, sheep, goats, etc.) and termites, from vegetation, as natural emissions from coal formations, from landfills and decomposing organic wastes, and, in highly variable amounts, from wetland rice cultivation. A significant amount also enters the air from leaks in natural gas pipelines. The rate of methane accumulation has been decreasing in an irregular fashion since the late 1980s, but with a major surge in 1998–99. The amount of methane in the atmosphere appears to have reached a natural balance, at about 1,800 parts per million by volume, and it is no longer increasing.

Despite the stabilization of the methane concentration, there are fears that a rise in ocean temperature might trigger the release of very large volumes of methane held as methane hydrates, which are pockets of methane enclosed inside ice crystals. Methane hydrates occur in sedimentary rocks, mainly beneath the sea floor but also in some areas on land, and the amount of methane they contain is estimated to equal 88 billion tons (8×10^{12} tonnes) of carbon. That is double the world's total reserves of peat, coal, oil, and gas combined. If a rise in temperature were to melt the ice, the methane would be released into the atmosphere. However, fears that a catastrophic release of methane from methane hydrates occurred about 55 million years ago (*see* PALEOCENE–EOCENE-THERMAL MAXIMUM) have now been discounted.

methyl chloroform (CH_3CCl_2) A chemical compound that was once used as a solvent. It is very toxic to humans and contributes to an enhanced GREENHOUSE EFFECT, having a global warming potential of about 700. It is also a source of free chlorine atoms that contribute to the depletion of stratospheric OZONE. At the fourth meeting of the signatories to the Montreal Protocol on Substances that Deplete the Ozone Layer (*see* APPENDIX IV: LAWS, REGULATIONS, AND INTERNATIONAL AGREEMENTS), held in Copenhagen in November 1992, it was agreed that the use of methyl chloroform should cease by January 1996.

microburst A strong downdraft that occurs below a fairly weak CONVECTION cell some distance from the center of a cumulonimbus storm cloud (*see* CLOUD TYPES). In 1975, Prof. Theodore Fujita (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), of the University of Chicago was the first person to recognize and name the phenomenon. The downdraft blows downward commonly at 25–55 MPH (40–88 km/h). When it strikes the ground, the air spreads to all sides as a strong horizontal wind. The effect is very local, extending for no more than 2.5 miles (4 km).

It is probable that the airflow in a microburst forms a VORTEX, with a downward spiral at the center intensifying the downdraft, and an upward spiral around the edge. This is called a "ring vortex." The upward curl in the airflow produces a ring of low air pressure. The ring vortex has been confirmed experimentally and has been observed in the dust or spray raised by microbursts.

The sequence of events in the development of a microburst begins with a shaft of rain or virga (*see* CLOUD TYPES) that is about 0.6 mile (1 km) in diameter and has very sharply defined edges. This generates a strong downdraft of air. The difference in BUOYANCY inside and outside the downdraft produces forces that start the air rotating. As the downdraft hits the BOUNDARY LAYER close to ground level, FRICTION causes the ring vortex to form. The downdraft then forces the ring vortex to expand, and as it does so it begins to spiral upward. Several ring vortices can form concentrically in a very strong microburst.

Microbursts represent a serious hazard to aircraft flying below about 1,000 feet (300 m), and since 1990 the Federal Aviation Authority has required most commercial pilots in the United States to undergo a program of education and training in the recognition of microbursts and techniques for avoiding or negotiating them. The area that is affected by a microburst is similar to the length of a runway at a major commercial airport. Aircraft are at greatest risk immediately after takeoff or when approaching to land.

As it flies through a microburst, the aircraft first experiences a strong headwind from the horizontal wind. About 10 seconds later the aircraft reaches the central part of the downdraft, where it experiences a strong downward force. A few seconds after that it experiences a tailwind as it reaches the horizontal wind on the other side of the center. The headwind increases the airspeed (speed in relation to the air, not the ground) of the aircraft, which also increases lift. The aircraft tends to climb and accelerate simultaneously. When it reaches the downdraft, its airspeed decreases and there is a loss of lift. The tailwind causes a further loss in airspeed and reduction in lift. Overall, the effect is first to lift and accelerate the aircraft and then to reduce its airspeed and throw it hard toward the ground. The difference between its airspeed in the headwind and tailwind is usually about 58 MPH (92.5 km/h), but in about 5 percent of the microbursts that have been documented the airspeed difference reaches about 105 MPH (169 km/h).

Microbursts can also capsize small boats. If one occurs over a forest fire it can produce a firestorm.

Further Reading

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microtherm A plant that grows in a microthermal climate (*see* CLIMATE CLASSIFICATION).

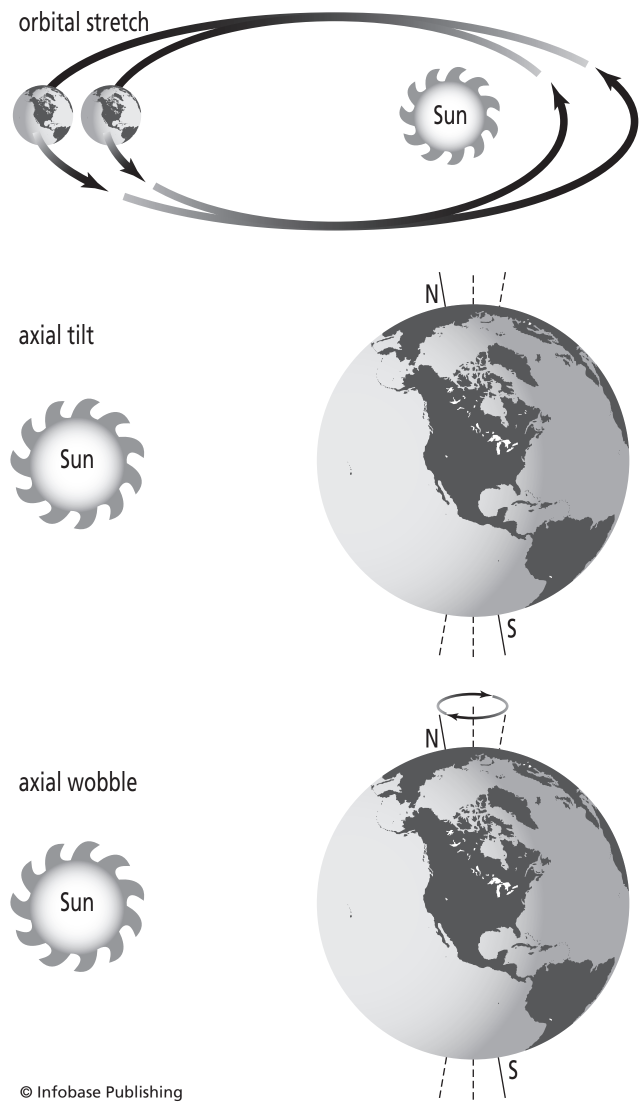
Milankovitch cycles Variations in the amount of solar radiation the Earth receives that are due to cyclical changes in the ORBIT of the Earth about the Sun and in the rotation of the Earth on its axis. Most climatologists accept that these changes affect the climate, in particular by triggering the onset and ending of GLACIAL PERIODS.

There are three such cycles, with different periods. Each has only a minor effect in itself but their influence is significant when all three coincide. They were first described in 1920, by Milutin Milankovitch (*see* APPENDIX I: BIOGRAPHICAL ENTRIES).

The first cycle involves changes in the Earth's orbit, which describes an ellipse with the Sun at one focus. Consequently, the distance between the Earth and Sun varies through the year that it takes to complete one orbit (*see* APHELION and PERIHELION). Because the Sun is not at the center of the path described by the Earth's orbit, the orbit is said to be eccentric. The shape of the ellipse is not constant, however. Gradually its ECCENTRICITY increases and then decreases, changing over a cycle with a period of about 100,000 years, which means this is how long it takes to return to any point in the cycle. At its most eccentric, the Earth is farther from the Sun at both aphelion and perihelion than it is when the orbit is less elliptical. At maximum eccentricity there is a difference of 30 percent between the distance between the Earth and Sun at perihelion and aphelion.

The second and third cycles affect the rotation of the Earth about its own axis. This axis is not at right angles to the PLANE OF THE ECLIPTIC—it is oblique. If it were at right angles (normal to the ecliptic), the Sun would be directly overhead at the equator at noon on every day in the year and there would be no SEASONS. At present the angle between the rotational axis and the plane of the ecliptic is about 23.45°, but this is not constant. Over a cycle of about 42,000 years its obliquity moves from 22.1° to 24.5° and back again. This does not alter the amount of radiation Earth receives from the Sun, but it does affect the way it is distributed. The greater the obliquity the more warmth high latitudes receive in summer, but the less they receive in winter.

Like a toy gyroscope or spinning top, the Earth also wobbles as it spins, taking about 25,800 years to complete each cycle, or full wobble. This alters the dates of the SOLSTICES and EQUINOXES. At present, perihelion occurs around January 3 and aphelion around July 4. In about 10,000 years from now these dates will be reversed because of the wobble in the axis. Then, the Northern Hemisphere will receive more solar radiation in midsummer and less in midwinter than it does now, and the Southern Hemisphere will receive less in midsummer and more in midwinter. These changes are also known as the PRECESSION OF THE EQUINOXES.



The Milankovitch cycles are three cyclical variations in the orbit and rotation of the Earth that trigger the onset and ending of glacial periods. Orbital stretch is a change in the eccentricity of the Earth's orbit. Axial tilt is the variation in the angle at which the north–south axis of the Earth is tilted with respect to the vertical. Axial wobble is the way the Earth's axis slowly turns around the vertical.

Milankovitch calculated the history of these astronomical cycles over the last several hundred thousand years. He found that the dates when the cycles were in phase, so all of them were exerting their maximum and minimum effects at the same time, coincided with the start and end of ice ages. This was confirmed in 1976, when studies of sediment cores taken from the ocean floor showed that climate changes had occurred at the times predicted by the Milankovitch mechanism.

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University of Montana. "Milankovitch Cycles and Glaciation." Available online. URL: www.homepage.montana.edu/~geol445/hyperglac/time1/milankov.htm. Accessed January 10, 2006.

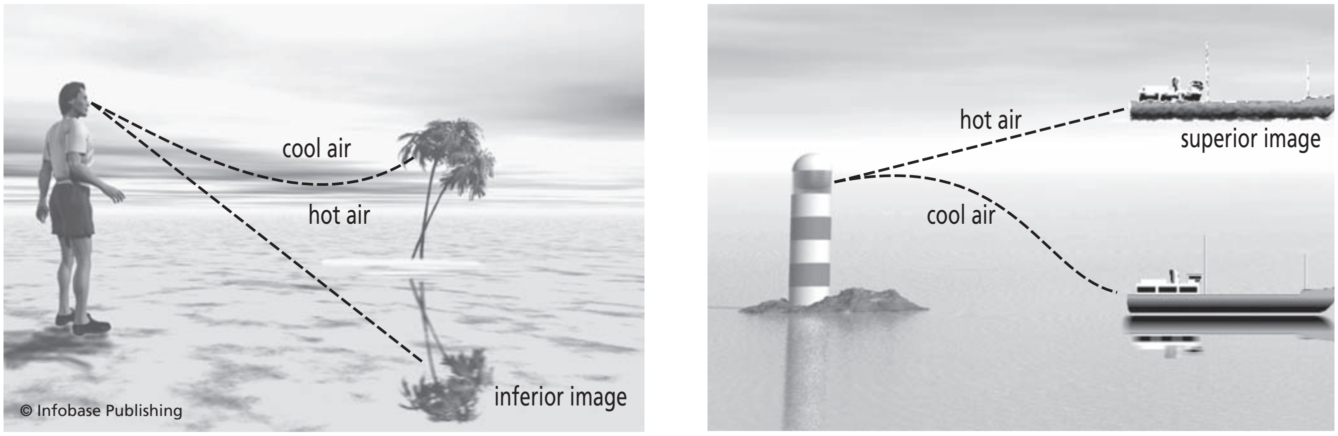
Miocene The first epoch of the Neogene period of the Earth's history, lasting from 23.03 million years ago until 5.3 million years ago. Climates during the Miocene were rather warmer than those of today, but they were becoming cooler, because the collision between India and Asia (*see* PLATE TECTONICS) that thrust up the Himalayan mountains altered the circulation of the air. This triggered a cooling that led eventually to the GLACIAL PERIODS of the PLEISTOCENE. The Rocky Mountains and the Andes also rose during the Miocene.

The modern GENERAL CIRCULATION of the atmosphere became established, and the isolation of Antarctica from Australia and South America allowed the Antarctic Circumpolar Current (*see* APPENDIX VI: OCEAN CURRENTS) to flow without interruption, as it does today. The Antarctic Circumpolar Current prevents warmer water from reaching the shores of Antarctica and moderating its climate. Consequently, the Antarctic ice cap continued to grow thicker.

Grasslands expanded throughout the Miocene as climates became cooler and drier. As the forests retreated, mammals that browse in forests became less numerous and grazing animals flourished. Ruminant mammals, with digestive systems adapted to deal with tough grasses, first appeared during the Miocene. Horses, camels, rhinoceroses evolved into species that thrived on the open pastures. The first deer, giraffes, mastodons, weasels, raccoons, cats, dogs, and hyenas appeared. There were fewer modern mammals than in the PLIOCENE epoch, which followed the Miocene, which is why this epoch was called "Miocene," meaning "less recent." *See* APPENDIX V: GEOLOGIC TIMESCALE.

mirage An optical phenomenon (*see* OPTICAL PHENOMENA) that is caused by the REFRACTION of light as it passes from cool to warm or warm to cool air. The most familiar example is the shimmer resembling a wet surface that appears on a hot day on a road ahead of the observer, but the most famous example is the palm-fringed lake that appears to thirsty travelers in a DESERT.

"Mirage," in *The Aerial World* by Dr. G. Hartwig, published in London in 1886 (Treasures of the NOAA Library Collection)



Light bends when it crosses a boundary between two bodies of air with different densities. The effect causes an observer to see a distant object apparently shifted to an incorrect position. This is a mirage. The object is real, but displaced downward to form an inferior image (left) or upward to form a superior image (right).

The image is not an optical illusion, and it can be photographed. Air in contact with a hot road or desert surface is at a higher temperature than air above it. As light from a higher level approaches the surface it is refracted in the opposite direction to the curvature of the Earth—away from the surface. A human observer assumes that light always travels in a straight line, so a low-level image appears of something at a much higher level. In the case of the road shimmer, the image is of the sky. In the case of the desert image, the palm trees are real, but the traveler also sees a second image of them. This is often inverted and looks like a reflection, implying the existence of water. The "water" and the "reflected" trees make up the mirage. Because both this mirage and road shimmer produce images below the position of the object that is its source, these are called "inferior images."

"Superior images" can also occur. In these cases, light passes from warmer to cooler air and is refracted in the same direction as the curvature of the Earth. Again, the observer assumes that light travels in a straight line and sees the image at a position higher than its source. This can make it possible to see a ship that is below the horizon and sometimes it can make an object appear to be above the surface, in which case it is said to be "looming."

Air may lie in layers at different temperatures, causing light to be refracted separately at each boundary. This can distort images, even to the extent of producing the impression of a mountain above the sea, and can also enlarge them.

The Fata Morgana is a mirage that occurs when atmospheric density increases with height within a thin layer of air lying above a cold surface, most commonly of the sea. Light is refracted to produce a greatly magnified superior image of distant buildings or cliffs that can sometimes resemble great castles partly in the sky and partly beneath the sea. The phenomenon is especially common in the Strait of Messina, between the Italian mainland and Sicily. This is the site associated with the mythical submarine palace of Morgan le Fay, or Fata Morgana, the fairy sister of King Arthur, of which the mirage is imagined to be the reflection.

The Fata Morgana is an example of towering, which is the vertical stretching of a mirage that occurs when the downward curvature of light due to refraction increases with altitude. To an observer, the distance between the top and bottom of the image is apparently increased.

mixing law When a volume of fluid containing several ingredients is mixed, each of them will become evenly distributed throughout the total volume. Once this condition is reached, further mixing will have no effect. This can be demonstrated by adding a small amount of pigment (such as food coloring) to water and then stirring the mixture. At first the colorant occupies discrete areas in the water, but very soon it becomes evenly distributed, the color of the mixture is uniform throughout, and further stirring does not alter the color.

model A simplified description of the way a complex process is believed to function. An example is the three-cell model of the circulation of the atmosphere (*see* GENERAL CIRCULATION), which explains how warm air moves away from the equator and is replaced by cool air from higher latitudes. This model is easy to visualize and understand, but it is very approximate and lacks detail, so its value is limited. More detailed models comprise sets of mathematical relationships that aim to simulate the processes which take place in a system, such as the atmosphere, and computers perform the necessary calculations. The simulation simplifies the system and accelerates or slows the rate at which the processes occur. This facilitates the study of the system. CLIMATE MODELS are of this type.

A hydrological model is used to simulate the behavior of real hydrologic systems, such as drainage basins and river flow. The model may be a small-scale physical device that mimics the real system, a computer simulation, or a sequence of mathematical calculations.

moisture Water that is present in the atmosphere. In CLIMATOLOGY, moisture is the amount of PRECIPITATION associated with a particular type of climate, or the effectiveness of that precipitation, which is the amount of precipitation minus the amount of water that evaporates from the ground surface. This can be measured as the moisture factor. In the THORNTHWAITE CLIMATE CLASSIFICATION the effectiveness of precipitation is used to calculate a precipitation-efficiency index. In METEOROLOGY, moisture is either the amount of WATER VAPOR present in the atmosphere or the total amount of water present as ice, liquid, or vapor in a given volume of air. The amount of water vapor in the air is known as the HUMIDITY of the air.

moment of inertia The equivalent of mass in calculations that involve a body that is rotating about an axis. It is calculated by multiplying the magnitude of each element of the body's mass by the square of its distance from the rotational axis.

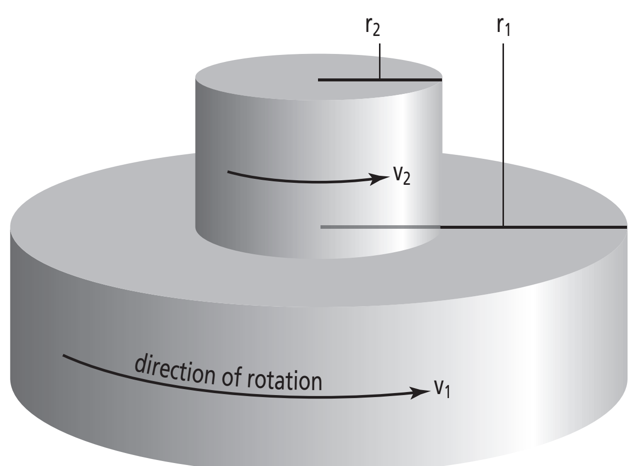
momentum The product (*mv*) of the mass (*m*) and speed (*v*) of a body that is moving in a straight line. For a moving body that is following a curved path, the equivalent term is angular momentum.

Absolute momentum, also known as absolute linear momentum, is the sum of the momentum of a particle in relation to the surface of the Earth and its momentum due to the rotation of the Earth. Both of these values are VECTOR QUANTITIES.

Angular momentum is the momentum of a body that is following a curved path. Angular momentum is conserved. This means that once a body possesses angular momentum, this momentum will remain constant provided no external force acts to accelerate or slow it.

The consequence of the conservation of angular momentum is seen at its most dramatic in the intense speeds generated near the center of a TROPICAL CYCLONE or TORNADO. Close to the center of these systems, air is spiraling upward. This produces a low-level region of low pressure and this low-pressure area draws in a flow from the surrounding air. As it spirals toward the center, the approaching air turns in a progressively smaller circle, and it accelerates because of the conservation of its angular momentum.

Three factors affect the motion of a body that is turning in a circular path about an axis: the mass of the body (*M*), the radius of its circle of turn (*r*), and the



Angular momentum: If air that is rotating in a large circle, radius r_1 at an angular velocity V_1, starts turning in a much tighter circle, radius r_2, it accelerates, so its new velocity V_2 is greater than V_1.

speed with which it is turning (V). Its speed of turn is known as its angular velocity. For any rotating body, the product of these is a constant:

$$MVr = \text{a constant}$$

The constant, MVr, is the angular momentum. Once the body is rotating, this constant is preserved. This means that if one or more of the three factors changes, then one or more of the others will also change automatically, in order to preserve the constant.

Suppose a body of air with a mass of one unit (M = 1) is rotating with an angular velocity (V_1) of 5 units in a circle with a radius (r_1) of 20 units.

$$MV_1r_1 = 1 \times 5 \times 20 = 100$$

Now suppose that the same air turns in a much tighter circle, with a radius (r_2) of 5 units. The angular momentum must be conserved, but the mass remains unchanged, so if the radius decreases the angular velocity must increase (and vice versa). This can be expressed as:

$$MV_2r_2 = 100$$
$$\therefore V_2 = 100 \div (Mr_2) = 20$$

Dividing the radius by 4 multiplies the angular velocity by 4.

A pirouetting ice skater can exploit the conservation of angular momentum if he or she begins to turn with the arms fully extended and then draws them inward, toward the body. This alters the radius of rotation and therefore, with no further effort on his or her part (no additional work is needed), the skater spins faster. At the end of the spin he or she slows down by extending the arms once more.

The Earth is a rotating body, and the atmosphere rotates with it. Within the total atmosphere, every mass of air possesses angular momentum. If a body of air moves toward or away from the equator, its radius of rotation will alter, because that radius is the distance between the air and the rotational axis of the Earth. Like the pirouetting skater, its angular velocity increases as it moves away from the equator and its rotational radius grows smaller. The change in its angular velocity produces a movement toward the east, in the direction of the Earth's rotation. If a body of air that was stationary over the equator moved to latitude 20°, it would then be moving eastward at about 66 MPH (106 km/h). FRICTION with the surface and air movements induced by pressure differences mask much of this effect, but the overall motion of the atmosphere is influenced by it.

monsoon A reversal in the direction of the prevailing wind (*see* WIND SYSTEMS) that occurs twice a year over much of the TROPICS, producing two seasons with distinctly different weather. The word *monsoon* is derived from the Arabic word *mausim,* which means "season." This became *monção* in Portuguese and *monssoen* in Dutch, from which language the word entered English.

A monsoon is nothing more than one of two very clearly defined seasons in the Tropics. One monsoon is very wet and the other is very dry.

Winds are the movement of air from areas of high surface pressure to areas of low surface pressure. If the wind changes direction, therefore, it means there has been a change in the distribution of pressure. This is the general explanation for the monsoons.

During winter, as the land cools and chills the air above it, surface AIR PRESSURE builds over large continents to produce very extensive ANTICYCLONES. Air is subsiding in all anticyclones, and as it sinks and warms by compression (*see* ADIABAT) its relative HUMIDITY decreases. The air is very dry when it reaches the surface, and it flows outward from the high-pressure region, preventing moister air from entering. This produces the dry winter monsoon.

At high altitude, near the tropopause (*see* ATMOSPHERIC STRUCTURE), air is moving into the region and sinking at the center. This produces a region of convergence and low pressure above the region of high pressure, and divergence at the surface (*see* STREAMLINES). Outside this region there are areas of low surface pressure and high pressure near the tropopause. These are over the sea, where the air temperature remains warmer than it is over land, because of the slower rate at which water cools, and warm air is rising.

In summer, the situation reverses. The land warms more quickly than the sea, producing a large area of low surface pressure. When the pressure over the continental interior is lower than the pressure over the sea, air moves from sea to land. As it crosses the

The regions of Africa and Asia that are affected by the monsoons

ocean, water evaporates into it, so the air is close to SATURATION by the time it reaches land. It rises as it moves over the continent and its water vapor condenses, releasing LATENT HEAT to sustain the instability of the air (*see* STABILITY OF AIR). This produces the giant cumulonimbus clouds (*see* CLOUD TYPES) and torrential storms of the wet summer monsoon. The monsoon low is the area of low surface pressure that develops over a continent during the summer and over the adjacent ocean during the winter.

The mechanism is very similar to that which produces LAND AND SEA BREEZES, but it operates on a much larger scale, and this type of circulation can develop only where conditions are fairly BAROTROPIC and a large landmass lies adjacent to a warm sea. These necessary conditions are met in Asia, but are only partly met in other continents. Tropical Africa and the eastern part of the Amazon basin in South America experience seasonal changes of a monsoon type, and there are distinct dry and wet seasons in parts of North America, but the reversals of wind direction are not strongly marked.

It is the Asian monsoons that produce the most extreme weather. This is because of the combined effects of the extremely large Asian landmass and the Himalayas. A monsoon TROUGH of low pressure forms during the summer (wet) monsoon at about latitude 25°N, and extends just to the south of the Himalayas, through Pakistan, northern India, and Bangladesh. Warm, moist air circulating cyclonically (*see* CYCLONE) around the trough encounters the Himalayas and other mountain ranges. It is forced to rise, producing very heavy OROGRAPHIC rain. At Mumbai, India, an average of 4 inches (104 mm) of rain falls during the dry, winter monsoon that lasts from October until May. During the wet, summer monsoon, lasting from June until September, the city receives 67 inches (1,707 mm).

The Himalayas form a barrier that confines the summer monsoon to the region to the south of the mountains, but air over the Tibetan plateau is being strongly heated, producing high pressure and divergence at high altitude. At the same time, the INTERTROPICAL CONVERGENCE ZONE (ITCZ) moves northward, to between 25°N and 30°N. Between them, these establish a distribution of pressure and temperature that generates an easterly JET STREAM, which increases the rainfall over southeastern Asia, the Arabian Sea, and the Horn of Africa. In autumn, the temperature difference between the land and sea weakens and the ITCZ moves south. Behind it the winds are predominantly westerly. These disrupt the circulation. The jet stream disappears and is replaced by the polar jet stream, centered over the mountains and bringing westerly high-level winds. The surface PRESSURE GRADIENT is from north to south, and the surface winds are from the north or northeast. The rain ceases and the winter monsoon commences, carrying very dry air down from the mountains and out across the lands to the south.

People in Southeast Asia and especially in India watch anxiously for the start of the summer monsoon. The arrival of the rain brings relief from the very hot, humid conditions that precede it, but for farmers the rain is essential. If the monsoon fails, or even if its start is delayed, harvests will be poor. The rains arrive suddenly, as the burst of monsoon, when the cool, dry weather of the winter monsoon gives way in a matter of a few hours to warm, humid air and heavy rain. Generally, the later they arrive the less rain the monsoon as a whole will bring.

Climatological Intra-Seasonal Oscillations (CISOs) are a series of weather cycles that bring alternately wet and dry conditions to regions affected by the Northern Hemisphere summer monsoon. Four CISO cycles occur between May and October. The first brings wet weather in the middle of May over the South China Sea and the Philippines, followed by dry weather in late May and early June. The wet weather of the second cycle occurs in the middle of June and marks the start of the monsoon over the western North Pacific. It is followed by dry weather in the first half of July. The third cycle brings wet weather to the western North Pacific in the middle of August, followed by dry weather, and the fourth cycle brings wet weather in the middle of October. The CISO propagates from the equator to the northern Philippines from May through July, then westward along latitude 15°N from 170°E as far as the Bay of Bengal during August and September.

There is much that scientists still do not know about the Asian monsoon. A major project to study the monsoon began in 1996, based at Nagoya University, Japan. It is called GAME, the GEWEX Asian Monsoon Experiment (GEWEX is the Global Energy and Water cycle Experiment).

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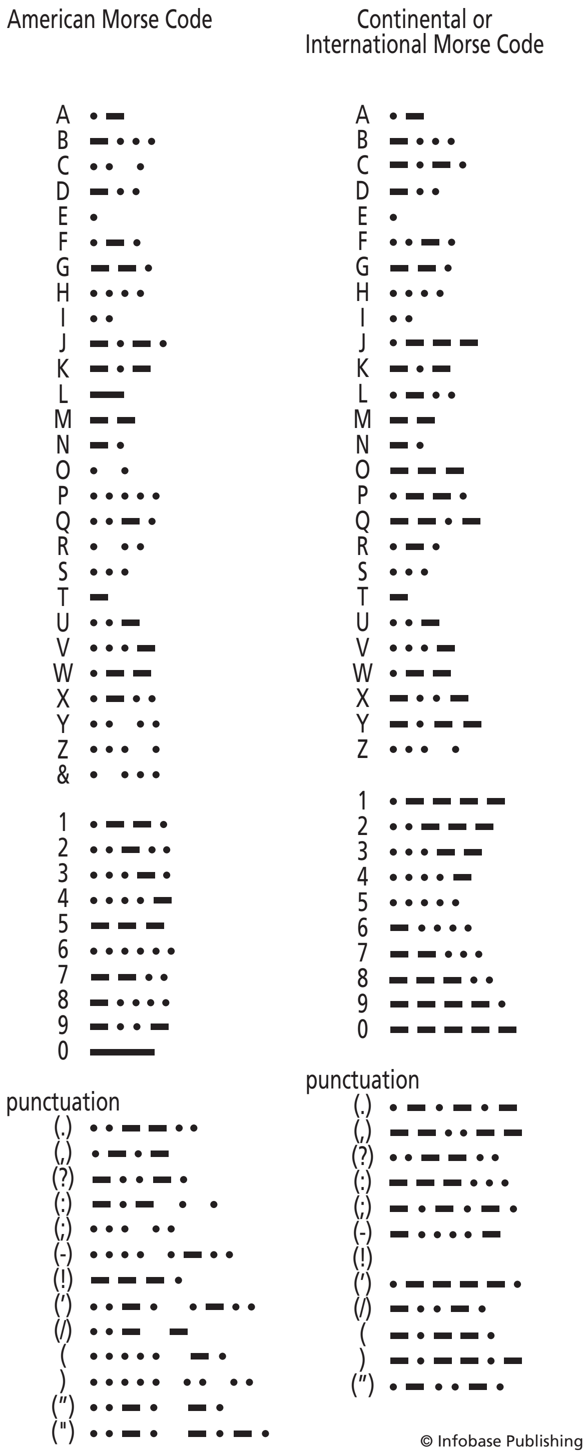
World Meteorological Organization, International Council for Science, and the Intergovernmental Oceanographic Commission of UNESCO. "Global Energy and Water Cycle Experiment." Available online. URL: www.gewex.org/index.html. Accessed January 10, 2006.

month degrees A measure of the conditions for plant growth that are associated with a particular type of climate. It is calculated by subtracting 43°F (6°C) from the mean temperature for each month and adding together the remainders (the number of degrees by which the temperature is above or below 43°F). The resulting total represents the number of degrees by which the mean temperatures are above or below 43°F in the course of the year, 43°F being the minimum temperature for growth of most plant species. Month degrees are used in some CLIMATE CLASSIFICATIONS.

Morse code A code that was devised by Samuel Morse (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) for the transmission of telegraph signals. He had developed it by 1838, and it was adopted throughout the world. When the telegraph began to be used to



The telegraphic code devised by Samuel Morse consists of patterns of long and short signals. It is easy to learn and efficient at conveying messages against background noise.

transmit meteorological data from outlying weather stations to central offices where they were assembled into weather reports and used to compile forecasts, Morse code was used to send them. It was also the code used to transmit radio communications to and from ships at sea and to and from aircraft. Some ships and aircraft were still using it in the 1940s. Although Morse code was designed to be sent and received as sound, the code could also be sent as flashes of light from a powerful, focused and directed lamp. In 1995, the U.S Coast Guard abandoned the code for communication with ships at sea. That marked the end of its general use for telegraphic communication, but it is sometimes used when conditions are poor and its simplicity and reliability make it attractive to amateur radio enthusiasts.

The code is made up of what are known conventionally as dots (•) and dashes (—). These make up units. One unit is equal in duration to one dot; one dash is equal to three units. One unit pause marks the space between the components of a character, a pause of three units separates the letters in a word, and a pause of six units separates words.

There are two versions of Morse code, the International and the American. Additional pauses are inserted between components of some characters in the American code, and some components are equal to four or six units. There is no code for an exclamation mark (!) or ampersand (&) in the International code.

multivariate analysis In statistics, the analysis of a number of measurements of different variable characteristics (such as TEMPERATURE, AIR PRESSURE, air DENSITY, and HUMIDITY) all of which refer to the same subject.

N

nadir The point on the surface that lies directly beneath an observational satellite.

National Hurricane Center (NHC) The center in Miami, Florida, that is part of the NATIONAL WEATHER SERVICE, and that maintains a continuous watch on TROPICAL CYCLONES over the Atlantic, Caribbean, Gulf of Mexico, and eastern Pacific Ocean throughout the hurricane season, which lasts from May 15 through November 30. The NHC prepares and issues hurricane watches and hurricane warnings (*see* WEATHER WARNINGS) for the public and specialist information for other users. Outside the hurricane season the NHC runs training courses for managers of emergency services from those parts of the United States and other countries that are affected by tropical cyclones. The NHC also conducts research aimed at improving hurricane forecasting techniques and it runs programs to raise public awareness of hurricanes, their dangers, and how to remain safe.

The NHC is one of six tropical cyclone forecasting centers that together monitor all tropical oceans for atmospheric disturbances that might develop into serious storms or tropical cyclones. Each center is owned and operated by the national authorities where it is located, and the work of all six centers is coordinated by the WORLD METEOROLOGICAL ORGANIZATION.

Nadi Tropical Cyclone Center, operated by the Fiji Meteorological Service, monitors the southwestern Pacific Ocean. Honolulu Tropical Cyclone Center, operated by the NWS in Hawaii, monitors the central North Pacific Ocean. The New Delhi, India, center, operated by the Indian Meteorological Department, monitors the Bay of Bengal and Arabian Sea. La Réunion Tropical Cyclone Center, operated by Météo-France, monitors the southwestern Indian Ocean. Tokyo Typhoon Center, operated by the Japan Meteorological Agency, monitors the western North Pacific Ocean and the South China Sea.

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National Meteorological Center The government center, in Washington, D.C., that specializes in numerical modeling of the weather. Its models are used in the preparation of forecasts and in studies of the behavior of the atmosphere.

National Oceanic and Atmospheric Administration (NOAA) An agency of the United States government, within the Department of Commerce, that is responsible for issuing short-term and long-term weather forecasts, operating U.S. meteorological satellites, conducting research, and performing such other tasks as are necessary in pursuit of these functions. Its task is defined as describing and predicting changes in the Earth's environment, and conserving and managing wisely the coastal and marine resources of the United States in order to ensure sustainable economic opportunities.

National Rainfall Index (RI) An index that is calculated country by country by weighting the national average PRECIPITATION according to the long-term averages of all the individual stations in the country. The resulting scale can be used together with other national indices, such as that for agricultural production, and it allows comparisons to be made between countries and years. Its disadvantage is that because it is calculated from precipitation, wetter areas have an undue influence on it, making it less useful when measuring the severity of drought.

National Severe Storms Forecast Center The establishment based in Kansas City, Missouri, that issues outlooks for the intensity of CONVECTION several times every day, covering all of the United States. Its convection outlooks provide warning of severe THUNDERSTORMS up to 24 hours in advance and where storms are likely to generate TORNADOES, appropriate warnings are issued for roughly six- or eight-hour periods.

National Severe Storms Laboratory (NSSL) The laboratory at which scientists study all aspects of severe weather. The laboratory is located at Norman, Oklahoma, but NSSL staff also work in Colorado, Nevada, Washington, Utah, and Wisconsin. The laboratory is part of the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION.

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National Snow and Ice Data Center (NSIDC) The organization that collects data and supports research relating to polar conditions and all aspects of ice, including PERMAFROST, paleoglaciology (*see* GLACIER), and ICE CORES. NSIDC keeps records of the extent of snow cover, AVALANCHES, glaciers, and ICE SHEETS. The center distributes data and information and publishes reports. It is part of the University of Colorado Cooperative Institute for Research in Environmental Sciences and is affiliated to the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION and the National Geophysical Data Center.

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National Weather Service The federal agency of the United States Government, forming part of the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, that is responsible for preparing and issuing weather forecasts and information on a range of hydrological matters, including river levels, tides, STORM SURGES, and TSUNAMIS. Its head office is at Silver Spring, Maryland, and it also maintains five major operating centers in various parts of the country. In addition to the published and broadcast forecasts for which it provides the meteorological data, the service also makes its information available online.

The Integrated Hydrometeorological Services Core is the branch of the NWS that combines all of the forecast and warning programs into a single core. The aim is to ensure consistency in the management and operation of each of the services. The core includes the Aviation Weather Program, Fire Weather Program (*see* FIRE), Public Weather Program, and TROPICAL CYCLONE PROGRAM.

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natural seasons Five periods, each lasting for at least 25 days, that are characterized by weather of a distinct type. These periods were identified by Hubert Lamb (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) from his studies of records for the British Isles from 1898 through 1947.

Spring–early summer lasts from early April until the middle of June. The weather is variable, but long settled spells are likely, with ANTICYCLONES in late May and early June.

High summer lasts from the middle of June until early September. It brings long spells of weather of different types, varying from year to year, but persistent cyclonic conditions (*see* CYCLONE) are more common than persistent anticyclonic conditions.

Autumn lasts from the middle of September until the middle of November. Long spells of settled weather occur. During the first half of the period these are mainly anticyclonic, and in the second half they are cyclonic and often stormy.

Early winter lasts from the third week in November until the middle of January. The weather is variable, but when long spells occur they usually bring mild, stormy weather.

Late winter and early spring last from the third week in January until the end of March. There are long spells of weather, but of types that vary from one year to another. In some years, this season resembles the middle of winter, and in others there is springlike weather from late in February.

Neoarchean The final era of the ARCHEAN eon of the Earth's history, which began 2,800 million years ago and ended 2,500 million years ago. Cyanobacteria were forming mats by the start of the Neoarchean. Cyanobacteria perform PHOTOSYNTHESIS, releasing oxygen as a by-product. By the end of the Neoarchean the accumulation of atmospheric oxygen was close to the level needed for atmospheric chemical reactions to be oxidizing rather than reducing. (*See* APPENDIX V: GEOLOGICAL TIMESCALE.)

Neogene The middle period of the CENOZOIC era of the Earth's history, which began 23.3 million years ago and ended 1.81 million years ago, with the commencement of the Pleistogene era. The Neogene comprises two epochs, the MIOCENE and PLIOCENE. It was toward the end of the Neogene that Iceland emerged, as a result of volcanic activity in the mid-ocean ridge in the floor of the North Atlantic Ocean.

An arctic ice cap began to accumulate during the Neogene, although it probably extended over western Canada and Greenland, without reaching the North Pole. The world's climates became steadily cooler through the Neogene, a trend that culminated in the GLACIAL PERIODS of the late Pliocene and Pleistocene. Continental climates also became drier and large deserts developed in central Asia and North Africa. (*See* APPENDIX V: GEOLOGICAL TIMESCALE.)

neon (Ne) A colorless gas that is one of the NOBLE GASES and forms almost no compounds. It is present in the atmosphere, accounting for 0.00182 percent by volume. The atmospheres of the other planets and satellites of the solar system have much less neon.

Neon vaporizes at -410.89°F (-246.05°C) and liquid neon freezes at -416.61°F (-248.67°C). Neon is extracted from the air industrially and used in neon lamps. The gas is sealed in a tube and an electric current is passed through it at 60–90 volts. This ionizes (*see* ION) the neon atoms around the cathode (negative electrode), causing the emission of a red light.

Neoproterozoic The final era of the PROTEROZOIC eon of the Earth's history, which began 1,000 million years ago and ended 542 million years ago. The Neoproterozoic is divided into three periods: the TONIAN (1,000–850 million years ago); CRYOGENIAN (850–630 million years ago); and EDIACARAN (630–542 million years ago). The supercontinent Rodinia broke up during the Tonian (*see* PLATE TECTONICS).

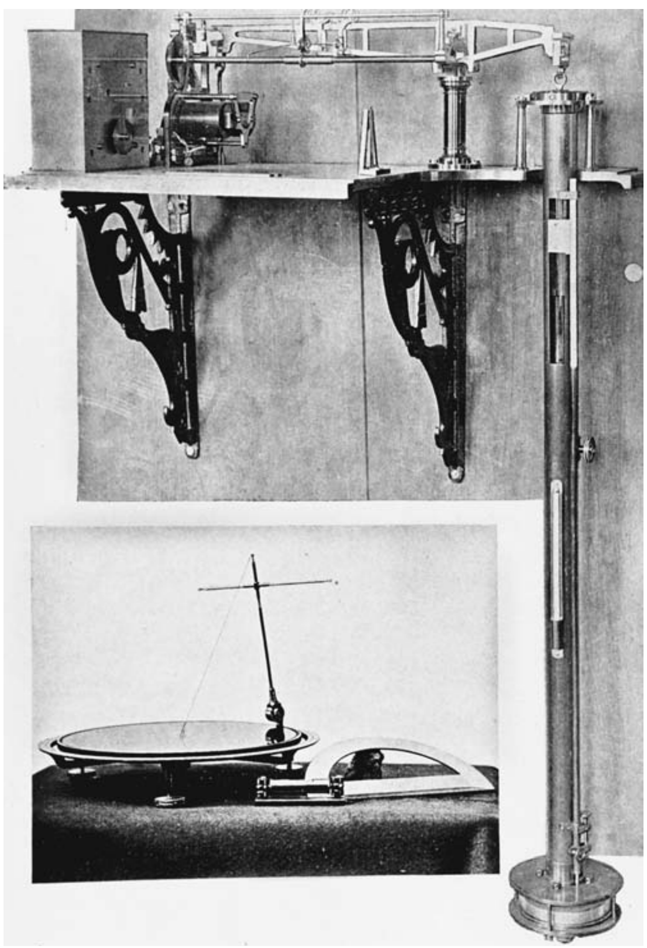
Multicellular organisms appeared near the start of the Neoproterozoic, and multicellular animals lived during the Ediacaran. Very little is known about the atmospheric concentrations of OXYGEN and CARBON DIOXIDE during this era.

There were between two and four GLACIAL PERIODS during the Cryogenian and early Ediacaran, but scientists are uncertain about how intense these were or how long they lasted. Some scientists believe that during these ice ages the entire surface of Earth was covered by ice, a condition they call SNOWBALL EARTH. (*See* APPENDIX V: GEOLOGICAL TIMESCALE.)

nephelometer An instrument that is used in remote sensing. It uses a laser beam to measure the SCATTERING of light by atmospheric particles. Nephelometer data are used to monitor VISIBILITY and air quality (*see* AIR POLLUTION). They are also used in studies of CLIMATIC FORCING by AEROSOL particles.

A nephelometer contains a small blower that draws in a continuous stream of air. The incoming air is heated before entering the body of the instrument to reduce its relative HUMIDITY to 40 percent. A halogen lamp illuminates the air and sensors measure the extent to which the light is scattered.

nephology The scientific study of clouds. *Nephos* is the Greek word for "cloud." In Greek mythology, Nephele was a phantom created by Zeus. She became a cloud goddess and married Athamas. He tired of her, preferring Ino, who hated Phrixus and Helle, the children of Nephele. To help her children escape from Ino who wished to destroy them, Nephele gave them a ram with a golden fleece that carried them to safety.



A Marvin nephoscope (lower left image) and Marvin barograph, from "The Aims and Methods of Meteorological Work," by Cleveland Abbe, in *Maryland Weather Service* published by Johns Hopkins University Press, Baltimore, in 1899 ***(Sean Linehan/NOS, NGS. Historic NWS Collection)***

In the modern world, satellite images reveal CLOUD TYPES and formations. The study of these images to obtain information about the weather systems that produced the clouds is called nephanalysis. Nephanalysis allows scientists to calculate the type and intensity of those systems and to track their movement. In nephanalysis, a line that is drawn to mark the boundary between clouds and clear sky, areas of PRECIPITATION, clouds of different types, or clouds at different heights, is called a nephcurve.

A nephoscope is an instrument used to measure the direction of movement of a cloud and its angular velocity around a point on the surface directly beneath it. If the height of the cloud is known, its linear direction can also be calculated. One widely used type, the Besson comb nephoscope, comprises a number of pointed rods, like the teeth of a comb, attached to the top of a long, vertical rod. The device is rotated until the cloud appears to be moving between the points, which allows the direction of movement to be measured. The Fineman nephoscope, in use in the 1880s, was a portable instrument used to measure the apparent speed of clouds across the sky. It had a circular black glass surface graduated with two concentric circles and lines radiating from the center, and a vertical pointer attached to the side. The instrument stood on its carrying box and was leveled by means of screw adjustments to its three feet. The pointer could be raised or lowered, and moved around the side. The pointer was aligned with a cloud so that the reflection of the cloud could be seen on the glass surface. The movement of the cloud could then be estimated from the movement of its reflection against the graduations.

Next Generation Weather Radar (NEXRAD) A network of Doppler RADAR installations located at weather stations, airports, and military airfields throughout the United States and operated by the NATIONAL WEATHER SERVICE. Each unit operates at frequencies of 2.7–3.0 GHz, emits a beam 1° wide, and has an antenna 25 feet (7.6 m) in diameter enclosed within a casing resembling a golf ball and mounted on top of a tall tower. It takes the radar five minutes to scan 360° in AZIMUTH and from 0–20° in elevation. It can detect and measure rainfall at a distance of up to 286 miles (460 km) and can measure the rate of rotation of a storm at up to 143 miles (230 km).

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Nimbus satellites A series of U.S. weather satellites, the first of which, *Nimbus 1,* was launched on August 24, 1964, followed by six more, *Nimbus* 7 being launched in 1978. Nimbus satellites carry equipment for Automatic Picture Transmission (*see* SATELLITE INSTRUMENTS), a television camera system for mapping clouds, and an infrared radiometer that allows pictures to be taken at night. The Nimbus series are second-generation satellites that followed the TELEVISION AND INFRARED OBSERVATION SATELLITE series.

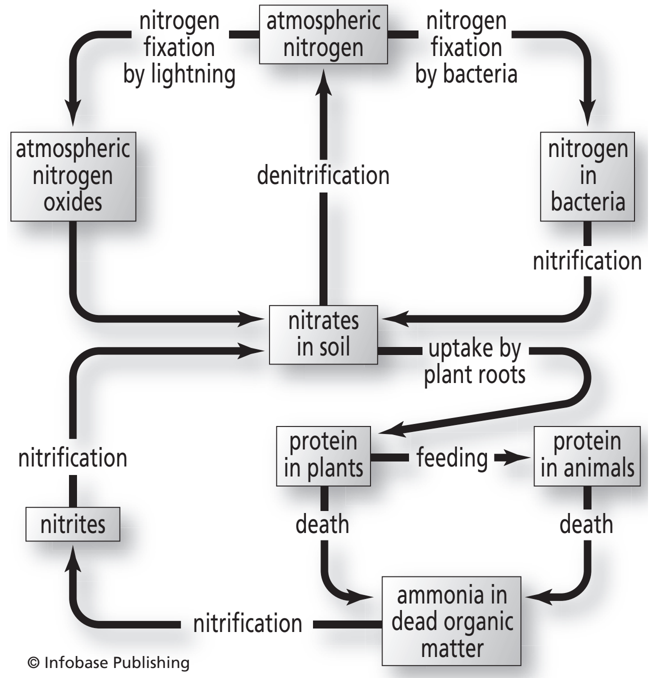
nitrogen (**N**) An element that as a colorless gas is the major constituent of the atmosphere, accounting for 78.08 percent by volume. Nitrogen freezes at -345.75°F (-209.86°C) and boils at -320.44°F (-195.80°C). There are two natural isotopes, ^{14}N and ^{15}N, the latter composing about 3 percent of the total amount of nitrogen. Chemically, nitrogen is fairly inert at the pressures and temperatures prevailing in the atmosphere, but it is oxidized by LIGHTNING and converted into ammonia (NH_3) and nitrates (NO_3) by bacteria; the process is called nitrogen fixation. Nitrogen is an essential component of all proteins and nucleic acids (DNA and RNA), and it is therefore essential for life.

Nitrogen fixation is the process by which gaseous nitrogen is converted into a soluble compound. This happens in three ways: by lightning, by BACTERIA, and industrially.

Lightning supplies the energy that is needed to make nitrogen react with OXYGEN. The resulting oxides are soluble and are washed to the surface by PRECIPITATION in the form of weak nitric acid (HNO_3).

The amount of nitrogen fixed in this way is minute compared with the amount that is fixed by bacteria. Several groups of bacteria fix nitrogen. All of them possess the enzyme nitrogenase, which catalyzes a reaction in which nitrogen (N_2) reacts with hydrogen (H_2) to produce ammonia (NH_3) at ordinary temperature and pressure:

$$N_2 + 3H_2 + \text{energy} \rightarrow 2NH_3$$



Atmospheric nitrogen is fixed by lightning and by bacteria. It is then used by plants and animals and finally it returns to the atmosphere.

Colonies of *Rhizobium* species form nodules on the roots of leguminous and some nonleguminous plants. Other species, including *Azotobacter* and *Clostridium* are free-living in the soil, as are the nitrogen-fixing sulfur bacteria belonging to *Chromatium, Rhodospirillum, Chlorobium,* and other genera. There are also species of *Nostoc, Anabaena,* and other species of cyanobacteria (formerly known as blue-green algae) which fix nitrogen in lakes and ponds.

Nitrogen is also fixed industrially to make nitrogen-based fertilizer. There are several techniques for doing this, all of which use a large amount of energy. In the widely-used Haber process, devised in 1908 by the German chemist Fritz Haber (1886–1934), air is heated to between 750°F and 930°F (400–500°C), at a pressure of about 677–845 inches of mercury (20–25 MPa, 200–250 atmospheres, or about 1¼–1½ tons per square inch) in the presence of a catalyst. Under these conditions nitrogen reacts with hydrogen to form ammonia by the reversible reaction:

$$N_2 + 3H_2 \leftrightarrow 2NH_3$$

Nitrogen fixation is one step in a sequence of reactions known as the nitrogen cycle by which nitrogen moves between the atmosphere, soil, living organisms, and returns to the air. The nitrogen cycle is one of the major cycles of elements.

The energy of lightning causes gaseous nitrogen to react with oxygen in the vicinity of the spark. This reaction produces NITROGEN OXIDES in a series of steps. The oxides then dissolve in RAINDROPS to form weak nitric acid (HNO_3). The nitric acid is washed to the ground, where it forms nitrates (NO_3).

Certain bacteria and cyanobacteria possess the ability to utilize gaseous nitrogen. Bacterial nitrogen fixation also leads to the formation of nitrates by the process of nitrification.

Nitrates are soluble and plants are able to absorb the soil solution through their roots. This is how they obtain most of the nitrogen they need to synthesize proteins, although there is evidence that plant roots also absorb organic compounds, consisting of much larger molecules derived from the decomposition of plant and animal material. Animals cannot manufacture proteins directly from nitrates. They obtain the proteins that their bodies need by feeding on plants (herbivores), on other animals (carnivores), or on both (omnivores).

Both plants and animals release waste products. These, together with their own bodies when they die, provide food for a hierarchy of soil animals, fungi, and bacteria. Through the process of decomposition, these organisms convert plant and animal proteins into ammonia (NH_3). Ammonia dissolves in water, and plants are able to use it directly in the form of ammonium (NH_4). However, ammonia can also combine with CARBON DIOXIDE (CO_2) to form ammonium carbonate ($(NH_4)CO_3$). Further nitrification by bacteria converts the ammonium carbonate into nitrites, in an oxidation reaction that releases energy:

$$(NH_4)CO_3 + 3O_2 \rightarrow 2NHO_2 + CO_2 + 3H_2O + \text{energy}$$

Nitrous acid (HNO_2) is unstable. It reacts with magnesium (Mg) or calcium (Ca) to form nitrites ($Mg(NO_2)_2$ or $Ca(NO_2)_2$). Other bacteria then nitrify the magnesium or calcium nitrite to form nitrates once more. This is also an oxidation reaction that releases energy.

$$2Ca(NO_2)_2 + 2O_2 \rightarrow 2Ca(NO_3)_2 + \text{energy}$$

The bacteria that perform nitrification reactions use the energy that these release to move and to digest food.

A final set of reactions returns nitrogen to the air as a gas. This process is called denitrification, and it is performed by another bacterial species, *Thiobacillus denitrificans*. Some species release gaseous nitrogen (N_2). Others release ammonia (NH_3). Ammonia is very soluble, but it boils at -29°F (-34°C), and consequently it vaporizes rapidly if it comes out of solution. Once in the air it is oxidized to nitrate, but most of the ammonia remains in the soil where it is captured by nitrifying bacteria, continuing in the cycle until it reaches *T. denitrificans* and is released as nitrogen gas.

The amount of nitrogen that leaves the air through nitrogen fixation is precisely balanced by the amount that is returned by denitrification. Denitrification completes the cycle.

This is the natural cycle, however, and it does not tell the whole story. The manufacture of nitrogen fertilizer involves fixing gaseous nitrogen industrially. The fertilizer is then released into the environment either as nitrates or as compounds that are converted to nitrates in the soil. Burning fuel at high temperatures and pressures also fixes nitrogen by supplying the energy needed to oxidize it to nitrogen oxides. Internal combustion engines are now a major source of nitrogen oxides, which react to form OZONE and PHOTOCHEMICAL SMOG as well as contributing to acid rain (*see* ACID DEPOSITION). The amount of nitrogen that is fixed and released industrially is now comparable to the amount moving through the natural cycle. This "industrial nitrogen" then joins the natural cycle, increasing the volume of nitrogen that is engaged in it.

nitrogen oxides **(NO_x)** Nitrogen forms seven oxides: nitrous oxide also called dinitrogen oxide (N_2O), nitric oxide also called nitrogen oxide (NO), nitrogen trioxide (N_2O_3), nitrogen dioxide (NO_2), dinitrogen tetroxide (N_2O_4), dinitrogen pentoxide (N_2O_5), and nitrogen trioxide also called nitrate (NO_3). Not all of these compounds are stable, and only N_2O, NO, and NO_2 are climatologically important.

The term *nitrogen oxides* (NO_x) refers specifically to NO and NO_2. The burning of fossil fuels (*see* CARBON CYCLE) and plant material is the principal source for atmospheric NO_x, especially vehicle exhausts and the burning of waste following forest clearance in the Tropics.

NO and NO_2 are catalysts for the formation of OZONE in the troposphere (*see* ATMOSPHERIC STRUCTURE), but they can cause the destruction of ozone in the stratosphere. NO and NO_2 are reversibly interchangeable through the gain or loss of an oxygen atom. This interchange takes place during the photolytic cycle (*see* PHOTODISSOCIATION) that both makes and destroys ozone. NO_x also play a critical role in the reactions that lead to the formation of PHOTOCHEMICAL SMOG.

At altitudes below about 15 miles (25 km), NO_x catalyze ozone formation. Above that height they catalyze its destruction. Stratospheric NO_x are produced by the oxidation of N_2O (nitrous oxide) present in the stratosphere:

$$N_2O + O \rightarrow 2NO$$

$$NO + O \rightarrow NO_2$$

The oxygen atoms result from the photolytic destruction of oxygen. After that, the reactions are:

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$O + NO_2 \rightarrow NO + O_2$$

These reactions can be summarized as:

$$2O_3 \rightarrow 3O_2$$

These reactions are not important in stratospheric ozone chemistry, because only a small amount of N_2O reaches the stratosphere. In the 1970s, there were fears that large fleets of commercial supersonic airliners would be developed. These aircraft would fly in the lower stratosphere and release NO in their exhausts and it was feared that this could cause ozone depletion. It did not happen because the supersonic fleets were not built. Today NO_x are important only because of their contribution to the formation of tropospheric ozone and photochemical smog.

Unlike the other oxides, N_2O does not react with the hydroxyl radical (OH). Reactions with OH remove most pollutants from the lower atmosphere by converting them to harmless compounds that are washed to the ground by PRECIPITATION. Because it remains unaffected by this process, N_2O is left to absorb infrared radiation (*see* SOLAR SPECTRUM), making it a greenhouse gas, with a global warming potential of 310 (*see* GREENHOUSE EFFECT). Its long lifetime also allows N_2O to drift into the stratosphere, where potentially it could become indirectly involved in ozone depletion.

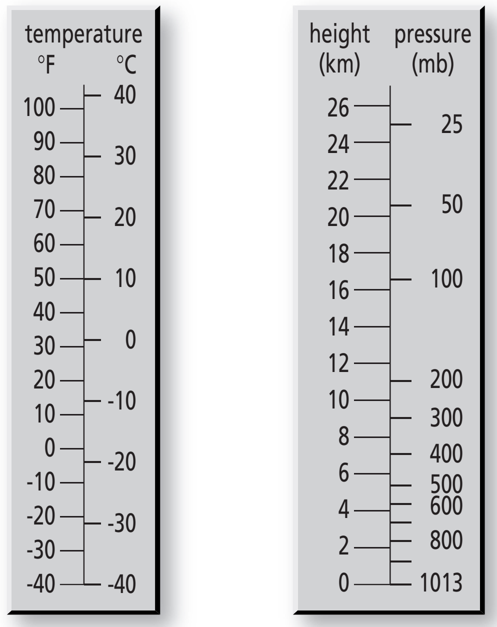
Nitrous oxide (N_2O) is present in the atmosphere at a concentration of 314 parts per billion by volume (measured in 1998). Approximately 60 percent of N_2O emissions occur in the Northern Hemisphere, and there is slightly more N_2O in the air over the Northern Hemisphere than there is in the air of the Southern Hemisphere. This concentration is increasing at a rate of 0.2–0.3 percent a year. The gas is released into the air naturally by bacterial action from soils in wet tropical forests and dry savannah grasslands and from the oceans. It is also released from certain industrial processes, including cattle and feedlots, burning of biomass, the manufacture and use of fertilizers, nitric acid, and nylon (adipic acid), and from automobiles fitted with three-way catalytic converters. Of all emissions, 54 percent are from natural sources and 45 percent result from human activity.

Once in the air, a molecule of N_2O remains there on average for 120 years and disappears by being broken apart by the energy of sunlight once it reaches the stratosphere. ICE CORES from the GREENLAND ICE CORE and EUROCORE PROJECTS show the atmospheric concentration of N_2O has changed more or less in step with climate changes since the end of the last ice age.

noble gases (inert gases) The chemical elements HELIUM (He), NEON (Ne), ARGON (Ar), KRYPTON (Kr), XENON (Xe), and RADON (Rn), which together make up group 0 (or group VIII) of the periodic table, are all chemically unreactive, although xenon and krypton do form a few compounds. The fact that they rarely combine with other elements, from which they seem to remain aloof, gave rise to their name of "noble" gases.

Argon is a major atmospheric constituent (*see* ATMOSPHERIC COMPOSITION). The others, apart from radon, are present in trace amounts. Radon is present in the air locally, but has a very short HALF-LIFE.

noise A signal that conveys no useful information and may obscure valuable data. The noise is said to be white if the signal producing it is random. Satellite observations of the surface are subject to noise caused, for example by winds that produce ocean waves and alter the emission of radiation from the ocean surface. Land contamination (*see* SATELLITE INSTRUMENTS) is a form of noise.



A nomogram is a diagram showing the relationship between two or more values. These examples compare Fahrenheit and Celsius temperatures and the change of atmospheric pressure with height.

nomogram A diagram that shows the relationship between two or more values or scales of measurement. Nomograms are produced in order to facilitate calculation by simplifying conversions between, for example, imperial and metric units or the Fahrenheit and Celsius TEMPERATURE SCALES. A nomogram can also show two types of measurement side by side, such as the change of atmospheric pressure with altitude.

Nordenskjöld line The Nordenskjöld line marks the boundary between boreal forest and tundra, and therefore indicates the highest latitude at which full-size trees are able to grow (small, stunted trees form part of the tundra vegetation). The line is drawn to link places where the mean temperature for the warmest month is high enough to produce tree growth and the mean temperature for the coldest month is not so low as to kill trees.

The line was first drawn by the Swedish geologist and polar explorer Otto Nordenskjöld (1869–1928; *see* APPENDIX I: BIOGRAPHICAL ENTRIES), who made detailed records of his expeditions to Greenland and the Yukon, as well as to the southern tip of South America and Antarctica. Nowadays the line separating forest and tundra can be seen on satellite images and so the Nordenskjöld line is little used.

normal The mean value of any meteorological value, such as TEMPERATURE or PRECIPITATION, calculated from measurements made at a particular place over a long period. This value is then taken to be the standard for that place, or the normal. For example, using measurements made over 51 years, the normal summer daytime temperature in Miami, Florida, is 86°F (30°C) and the average winter rainfall is 10 inches (250 mm). In mathematics, the word *normal* means "at right angles."

normalize To produce a dimensionless ratio (*see* DIMENSIONLESS NUMBER) between two quantities by dividing one quantity by a more fundamental quantity in the same dimensions. Any quantity divided by itself is equal to 1. Consequently, dividing a dimension by itself also yields 1 and the dimension disappears.

Normalized Difference Vegetation Index (NDVI) An index that measures the amount of actively photosynthesizing plant biomass in a landscape. It is shown in maps compiled from data supplied by an advanced very high resolution radiometer (*see* SATELLITE INSTRUMENTS).

The NDVI is the ratio (I - R) ÷ (I + R), where I is the amount of radiation received by the satellite in the near-infrared wavelength of 0.725–1.10 µm and R is the amount of radiation at the red wavelength of 0.58–0.68 µm. Healthy vegetation reflects most of the near-infrared radiation falling on it, but absorbs most of the red radiation (which is used in PHOTOSYNTHESIS). "Difference" in the name refers to the first part of the calculation, I - R. "Normalized" refers to the fact that this is divided by I + R.

Further Reading

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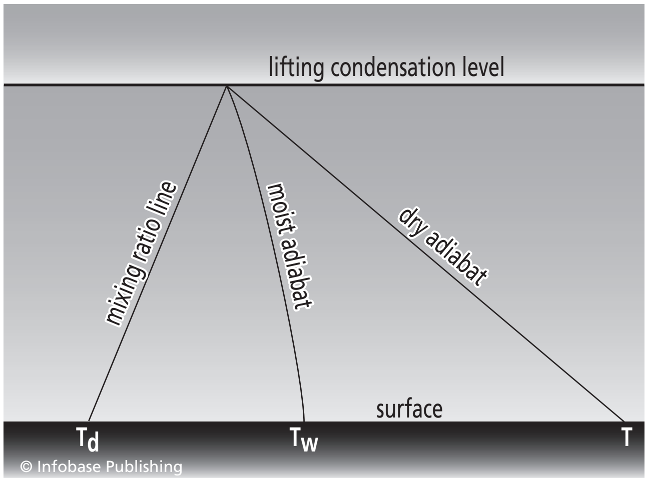
Normand's theorem A rule that was proposed in 1924 by the meteorologist C.W.B. Normand. The rule states that the height of the lifting condensation level (*see* CONDENSATION) can be shown by the intersection



Lines drawn on an aerological diagram can be used to indicate the height of the lifting condensation level.

of two lines on an aerological diagram (*see* THERMODYNAMIC DIAGRAM).

If the dry ADIABAT is drawn from a point on the surface at the ambient temperature T and the saturation MIXING RATIO is drawn as a line from the surface DEW point temperature T_d, the two lines will intersect at the lifting condensation level. If a SATURATION adiabat (also known as a moist adiabat) is drawn from the point of intersection to the surface, the point where it meets the surface will mark the wet-bulb TEMPERATURE T_w.

The theorem is derived from the fact that the amount of energy consumption that accounts for the difference between the saturation and dry adiabats is the same as that which accounts for the difference between the dry- and wet-bulb temperatures.

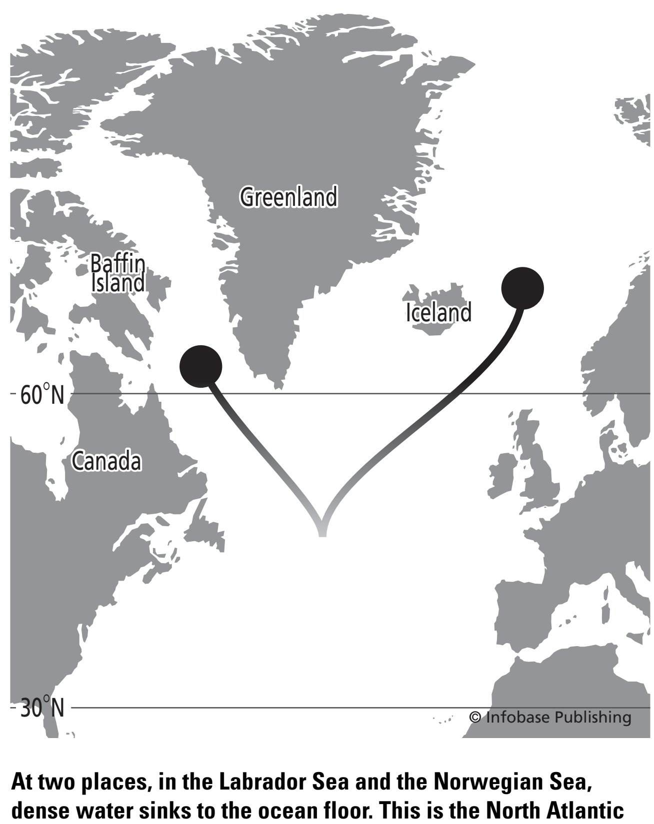
North American high A weak area of high surface pressure that covers most of North America in winter.

North Atlantic Deep Water (NADW) The cold, saline, dense water that drives the GREAT CONVEYOR. The NADW forms mainly in two places, in the Norwegian Sea to the northeast of Iceland and in the Labrador Sea, between Canada and Greenland.

The NADW begins close to the edge of the SEA ICE. When seawater freezes, the crystallization process expels the salt that was held by the water molecules while they were in the liquid phase. Seawater ice is fresh (but may taste salty because of brine trapped in spaces between ICE CRYSTALS) and the expelled salt increases the salinity of the seawater adjacent to the ice. The average salinity of the Atlantic Ocean is 34.9 per mil (parts per thousand), but that of the water adjacent to the newly formed sea ice is up to 35.5 per mil. Its increased load of salts makes the water denser.

The water near the ice is slightly warmer than 35°F (2°C). Seawater with a salinity of 35 per mil freezes at about 28.6°F (-1.91°C), and its density is greatest at just above 32°F (0°C). Water at this temperature is denser than the water farther from the ice, so it sinks beneath the less dense water and its place is taken by warmer, less saline, surface water that flows northward.

A ridge extends along the ocean floor between Greenland and Scotland. The NADW fills the basin on the northern side of the ridge then spills over the ridge between Iceland and Scotland. It is then known as Iceland Scotland Overflow Water (ISOW). ISOW is denser than the water of the deep ocean, and it sinks all the way to the floor at a depth of about 10,000 feet (3,000 m). As more water sinks behind it, the deep water forms a current that flows southward at an aver-



At two places, in the Labrador Sea and the Norwegian Sea, dense water sinks to the ocean floor. This is the North Atlantic Deep Water.

age speed of about 0.5 inches per second (1.4 cm/s), closely following the edge of the North American continent (which is several hundred miles from the coast). It takes more than 20 years for the water to reach the equator.

Farther south, more water joins the NADW. This flows from the Mediterranean Sea. Because of its warm climate, the rate of EVAPORATION is very high over the surface of the Mediterranean and the sea loses more water by evaporation than it receives from rainfall and from the rivers that flow into it. Evaporation makes the Mediterranean water very saline and therefore dense. The evaporative loss draws in water from the Atlantic through the Strait of Gibraltar. The inflow enters at the surface and floats above the saltier Mediterranean water, which sinks to the floor. The inflow is balanced by the outflow of salty water through the Gibraltar Strait at a depth of 3,300–6,600 feet (1,000–2,000 m). Two currents flow through the Gibraltar Strait. A surface current flows into the Mediterranean, and a deep current flows beneath it, out of the Mediterranean, moving at about 6.5 feet per second (2 m/s). The water of the deep current joins the NADW.

The total flow rate of the NADW is about 530–700 million cubic feet per second (15–20 million m^3/s). Because it formed at the surface and sank fairly quickly, the water is rich in dissolved OXYGEN (but poor in nutrients for marine organisms). Its dissolved oxygen ventilates the entire ocean and remains near the ocean floor for less than 200 years before returning to the surface.

Eventually the NADW reaches the Antarctic Circumpolar current (*see* APPENDIX VI: OCEAN CURRENTS) and becomes part of it.

The NADW plays an important role in regulating the climate, especially the climate of northwestern Europe. From time to time in the past its flow has changed, and there is evidence linking these changes to climatic events, including the LITTLE ICE AGE, MEDIEVAL WARM PERIOD, a cold period that occurred during the Dark Ages, and a warm period that occurred in Roman times. These changes seem to follow a cycle with a period of about 1,500 years (*see* STOCHASTIC RESONANCE). When the climate grows warmer, more icebergs (*see* SEA ICE) drift south and melt, producing a layer of freshwater that floats above the seawater and inhibits the formation of cold, saline water that will sink to form the NADW. However, suppressing the formation of NADW may also suppress the Great Conveyor, which brings warm water northward as the Gulf Stream and its branch the North Atlantic Drift, which continues as the Norwegian Current. A complete shutdown of the Conveyor might trigger a cold period, such as the Little Ice Age. This is the apparently paradoxical process by which GLOBAL WARMING could bring cooler conditions to the Northern Hemisphere.

North Atlantic Oscillation (NAO) A periodic change, or oscillation, that takes place on a scale of decades in the distribution of sea-level atmospheric pressure between Iceland and the Azores. There is no regular pattern to the NAO.

The usual pattern is of low pressure over Iceland and high pressure over the Azores. Air circulates in a counterclockwise direction around the ICELANDIC LOW and clockwise around the AZORES HIGH. Consequently, air between the low and high is driven in an easterly direction. It is this distribution of pressure that drives the North Atlantic wind and storm systems. Its strength varies, however, and when pressure is lower than the average over Iceland, it tends to be higher than average over the Azores, and vice versa.

The pattern is measured according to an NAO index. When pressure is lower than average over Iceland and higher than average over the Azores, the index is high. When the Icelandic low and Azores high are both weaker than average, the index is low. A high index brings cold winters to the northwestern Atlantic and northeastern North America, mild winters in Europe, and dry weather in the Mediterranean region. The NAO index remained high during much of the 1970s and was especially high from the late 1980s to 1995. In 1996, the index fell to a very low value.

Climate scientists believe the NAO is part of the much larger ARCTIC OSCILLATION and, because it affects climates throughout the Northern Hemisphere, the NAO is also known as the Northern Hemisphere annular mode.

Further Reading

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nuclear winter A scenario that was proposed in 1983 by a team of scientists led by Richard P. Turco to warn politicians of the possible climatic consequences of a full-scale thermonuclear war. The team assumed that the war would be fought entirely in the Northern Hemisphere and that it would involve the detonation of approximately one-third of the global stock of nuclear weapons. At that time there were more than 50,000 such weapons with a total explosive power equal to about 15,000 megatons of TNT.

The initial flash of heat and ionizing radiation (*see* ION) from the explosions would ignite fires. Most of these would be extinguished by the blast wave following the radiation flash, but electrical sparks and smoldering remains would then re-ignite them and eventually a cloud of black smoke would envelop the hemisphere. The smoke would absorb incoming solar radiation. This would warm the smoke and the air containing it, causing the cloud to rise, and a substantial amount of smoke would enter the stratosphere (*see* ATMOSPHERIC STRUCTURE). Smoke that entered the stratosphere would remain there for many months or even years, because particles in the stratosphere cannot be washed to the surface by rain or snow.

As the smoke rose, it would produce a region of low atmospheric pressure beneath the cloud. This would generate winds that would blow some of the smoke into the Southern Hemisphere. Early calculations suggested that the shading of the surface by the smoke cloud would reduce summer temperatures to levels typical of winter. This gave rise to the name "nuclear winter."

The fall in TEMPERATURE would cause the area of ocean covered by ice to expand. The frozen sea would have a climate similar to that on dry land, with more extreme winter temperatures. This positive FEEDBACK would intensify the global cooling and prolong the "winter."

PRECIPITATION over land would be reduced throughout the Northern Hemisphere and the Asian MONSOONS would fail. These climatic changes in addition to the cold would cause catastrophic harvest failures that would be followed by worldwide famine.

The study was meant as a warning, not a firm prediction, and it was based on a number of assumptions about the time of year the war took place, the distribution of targets, and the scale of the fires. Obviously, the calculations could not be tested.

The initial paper on nuclear winter led to further studies by a number of organizations. These confirmed the broad idea, but found that conditions would be more like those of late fall than of winter. This would still be severe enough to cause major harvest failures. It has also been calculated that 1 percent of the global stockpile of nuclear weapons would be sufficient to produce these effects if oil refineries were among the primary targets.

Since the first study was published, tensions have been reduced between East and West. More than enough weapons remain, however, to produce a "nuclear fall" if they were to be used.

Nusselt number A DIMENSIONLESS NUMBER, related to the RAYLEIGH NUMBER, that is used in calculations of the transfer of heat in fluids. It is the ratio of heat that is transferred to the amount that would be transferred by pure conduction under ideal conditions. The number was discovered by the German physicist Ernst Kraft Wilhelm Nusselt (1882–1957; *see* APPENDIX I: BIOGRAPHICAL ENTRIES).

O

oasis effect The cooling effect that produces a difference in local weather found where an area of moist ground (an "oasis") is surrounded by dry ground ("desert"). The effect is due to cooling caused by EVAPORATION.

Over the moist ground, kept moist by irrigation or because the water table (*see* AQUIFER) is at or above ground level, the rate of evaporation exceeds the rate of PRECIPITATION and the warm air over the ground supplies the LATENT HEAT of vaporization. In the surrounding area, which is dry, evaporation and precipitation balance, but because the amount of precipitation is low, the rate of potential evaporation exceeds that of precipitation. Surplus heat is absorbed by the ground and warms the air in contact with the surface. This produces a large positive BOWEN RATIO over the dry ground and a negative Bowen ratio over the moist ground. Air is subsiding over the moist ground and rising over the dry ground. The oasis effect occurs not only at desert oases, but also over large, irrigated fields in areas with a semi-arid climate. (*See* ADVECTION.)

occlusion The stage in the life cycle of a frontal system (*see* FRONT) at which the advancing cold air has started to lift the air in the warm sector clear of the surface. This is depicted on a WEATHER MAP as the cold front overriding the warm front, and it is shown as a front with alternating triangles and semicircles. An occlusion in which the cold front first starts to overtake the warm front some distance from the peak of the WAVE DEPRESSION is known as a seclusion.

Air on all sides of the warm sector is cold in relation to the warm-sector air, but in fact the air on one side of the warm sector is colder than that on the other side. Instead of classifying air as simply warm or cold, therefore, a third category of cool has to be introduced. It is then possible to classify an occlusion as warm if its passage brings a transition at the surface from cold to cool air, and as cold if it brings a change from cool to cold air.

An occlusion that has reversed its direction of motion because either a new CYCLONE has formed or the old cyclone has been shifted is known as a backbent occlusion, also called a bent-back occlusion.

The center of a DEPRESSION associated with fronts that have occluded is called a cold core. At this stage the temperature difference between the warm air at the center and the cooler surrounding air has disappeared and the depression is located on the poleward side of the warm AIR MASS.

An occlusion that forms when an advancing warm front reaches a mountain range that acts as a barrier to it is called an OROGRAPHIC occlusion. The front slows, causing the air in the warm sector to accumulate in a pool and allowing the cold front to undercut it more rapidly than it would have done over level ground.

The descent of dry air over an occlusion and ahead of the upper-level front is known as a prefrontal surge. The air that descends over an occluded front from near the top of the troposphere (*see* ATMOSPHERIC STRUCTURE) is called a dry slot; it is a prefrontal surge only if it is ahead of the front. The dry air lies above relatively warm, moist air. This situation can cause instability (*see* STABILITY OF AIR), resulting in the formation of cumulonimbus clouds (*see* CLOUD TYPES) and sometimes THUNDERSTORMS.

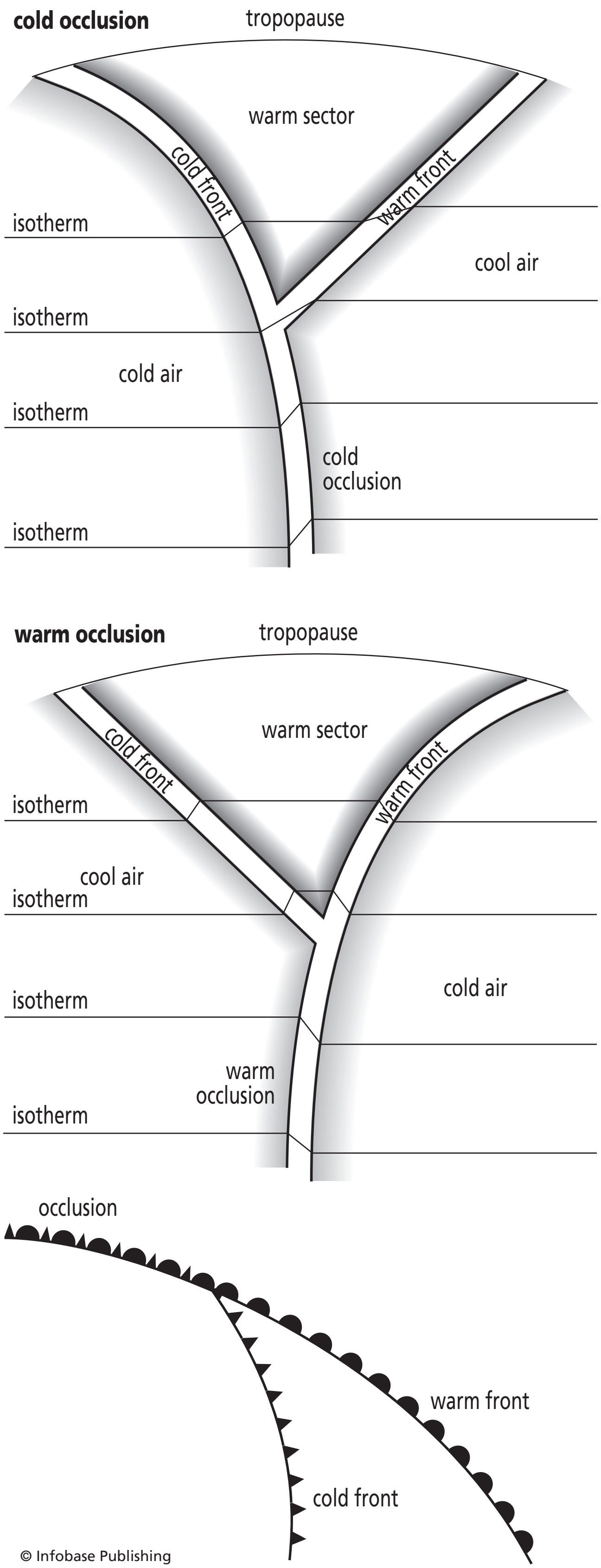
occultation The passing of one celestial object in front of another, so that one of the objects is partly or completely hidden to an observer. For example, the Moon and Sun hide the stars by passing in front of them, and planets hide their satellites in the same way.

Planetary atmospheres can be studied during occultations. As the planet passes in front of a star, light from the star passes through the planet's atmosphere on its way to an observer on Earth. The spectrum of the light received at the observatory reveals the chemical elements present in the atmosphere through which the light passed.

ocean Salt water covers approximately 70.8 percent of the Earth's surface and approximately 75 percent of all seawater is at a temperature between 32°F and 39°F (0–4°C). Because of the high thermal inertia (*see* HEAT CAPACITY) of water, the oceans exert a strong moderating influence on air temperatures and ocean currents (*see* APPENDIX VI: OCEAN CURRENTS) play an important climatic role by transporting heat from the equator into high latitudes.

That part of the ocean where the temperature is lower than 46°F (8°C) is called the cold water sphere, also known as the oceanic stratosphere. This is the oceanic equivalent of the stratosphere (*see* ATMOSPHERIC STRUCTURE). The warm water sphere is the part of the oceans where the temperature is higher than 46°F (8°C).

Oceanographers recognize three major oceans: the Atlantic, Pacific, and Indian. The Arctic Ocean is counted as part of the Atlantic and the Southern Ocean as part of the Atlantic, Pacific, and Indian Oceans, with arbitrary boundaries separating them. In addition, there are smaller seas and bays seas adjacent to the major oceans.



An occlusion is the condition in which warm air is rising above cold air and all of the warm air has risen above ground level. This is represented on a weather map by a line alternating the symbols for a warm and cold front, both on the same side of the line of the front. If the air behind the occlusion is colder than the air ahead of it, it is a cold occlusion. If the air behind the occlusion is less cold than the air ahead of it, it is a warm occlusion.

Ocean areas, volumes, depths

Ocean	Area		Volume		Mean depth	
	10 × 6 miles²	10 × 6 km²	10 × 6 miles³	10 × 6 km³	miles	km
Atlantic						
Excluding seas	31.82	82.44	77.6	323.61	2.44	3.93
Including seas	41.09	106.46	85.10	354.68	2.07	3.33
Pacific						
Excluding seas	63.78	165.25	169.77	707.55	2.66	4.28
Including seas	180.06	179.68	173.65	723.70	2.50	4.03
Indian						
Excluding seas	28.35	73.44	69.83	291.03	2.46	3.96
Including seas	28.92	74.92	70.05	291.94	2.42	3.90
All oceans (including seas)						
	139.37	**361.06**	**328.80**	**1,370.32**	**2.36**	**3.79**

The table above lists the three oceans, showing their areas (in millions of square miles and millions of square kilometers), volumes (in millions of cubic miles and millions of cubic kilometers), and mean depths (in miles and kilometers). Two sets of figures refer to the oceans with and without their adjacent seas.

oceanicity The extent to which the climate of a particular place resembles the most extreme type of maritime climate. Although climates can be classified as continental or maritime (*see* CLIMATE TYPES), these types grade from one into the other. Except on ocean islands and some, but not all, coasts, a place with a maritime climate also experiences more continental conditions for some of the time. Similarly, maritime influences extend a long way inland from the coasts of continents.

There is a need to refine the classification of continental and maritime climates in a way that reflects the gradations between them. The differences can be shown clearly on a HYTHERGRAPH, but only in a relative sense. The hythergraph compares the climates of two or three places (including more makes the graph too cluttered to be easily read), but gives no absolute value for their types of climate. This is possible if the essential climatic features of an area, together with its latitude, can be used to calculate a climatic index. Indices of CONTINENTALITY are widely used. These rate the continentality of a climate on a scale where 0 indicates an extreme maritime climate and 100 an extreme continental climate. It is possible, therefore, to define the oceanicity of a climate as a low value for its index of continentality.

It is not entirely satisfactory to define something only by its difference from something else, however, and several attempts have been made to devise an index of oceanicity. It is possible to calculate oceanicity as a percentage from the number of occasions in the year when the area being considered lies beneath maritime air compared with the total number of AIR MASSES that affect it during the same period. In this calculation:

$$O = (M/N) \times 100$$

where O is the index of oceanicity, M is the number of maritime air masses affecting the area in a year, and N is the total number of air masses affecting the area in a year.

Two other methods are also widely used. Both of them base the calculation on the TEMPERATURE range and one also takes account of PRECIPITATION. This method is given by:

$$O = P\, d_t/100\Delta$$

where P is the average annual precipitation in millimeters, d_t is the number of days on which the temperature is in the range 0–10°C, and Δ is the difference in temperature between the warmest and coldest month, in degrees Celsius.

The other method is given for the Northern Hemisphere by:

$$O = 100\, ((T_o - T_a)/A)$$

where T_o is the mean monthly daytime temperature for October, T_a is the mean monthly daytime temperature for April, and A is the average daytime temperature range. For places in the Southern Hemisphere, $T_a - T_o$ should be substituted for $T_o - T_a$. This index represents oceanicity as a percentage, with 0 indicating an extreme continental climate and 100 indicating an extreme maritime climate.

Fiji, which is an oceanic island, obviously has a maritime climate. Its oceanicity index is 67. Thorshavn, in the Faeroe Islands, has an oceanicity index of 31. Omaha, Nebraska, has a continental climate. Its oceanicity index is 6.

Older Dryas A cold period that occurred in northern Europe from about 12,200 years ago to about 11,800 years ago, soon after the ice sheets had retreated at the end of the Devensian GLACIAL PERIOD. It followed the Bølling INTERSTADE and was first recognized from clays at a tile-making factory at Allerød, north of Copenhagen, Denmark. The clays are rich in remains of mountain avens (*Dryas octopetala*), an arctic-alpine plant.

Oligocene The epoch of geologic time (*see* APPENDIX V: GEOLOGIC TIMESCALE) that began 33.9 million years ago and ended 23.03 million years ago. It is the most recent epoch of the PALEOGENE Period.

The climates of the world began to grow cooler during the Oligocene, but with a slight rise in temperatures toward the end of the epoch. ICE SHEETS started to form in Antarctica, causing sea levels to fall, and the TROPICS decreased in size, with broad-leaved tropical evergreen forest giving way to temperate, deciduous woodland of evergreen and broad-leaved trees. This type of woodland survives in a few places in North Island, New Zealand, and the tip of South Africa. Grasses became more widespread. In North America, subtropical plants such as cashews and lychees grew alongside temperate plants such as roses, beech, and pine.

The largest animals were the odd-toed ungulates (perissodactyls). The hornless rhinoceros (*Indricotherium*) of central Asia weighed up to 27.5 tons (25 tonnes), making it the largest land mammal that has ever lived. Ancestors of the elephants appeared in Africa.

optical air mass (airpath) The length of the path through the atmosphere that is traveled by light from the Sun or any other celestial body. It is expressed as a multiple of the path length traveled by light when the source of the light is directly overhead (at the zenith).

Optical depth, also called optical thickness, is a measure of the extent to which a cloud or layer of the atmosphere prevents the vertical passage of solar radiation. It can be applied to any layer of interest and is expressed as a DIMENSIONLESS NUMBER, rather than a linear measure in feet or meters.

Optical depth is calculated from the ratio of the amount of radiation falling on the upper boundary of the layer (I_t) to the amount emerging at the bottom (I_b), by the equation: $I_t/I_b = \exp(-\tau/\cos Z)$, where τ is the optical depth of the layer and Z is the zenith angle, which is the angle between the solar radiation and the vertical. At sunrise and sunset $Z = 0$. A layer is considered to be optically thin if τ is less than about 0.2–0.5 and thick if τ is greater than 1.0.

optical phenomena In addition to the blue sky, clouds, and PRECIPITATION that are commonplace, the sky occasionally displays more unusual phenomena. Rainbows are a familiar example, but there are others that are less familiar, some of them alarming to those who have not seen them before and do not understand what causes them. A selection of these phenomena are described and explained below. For convenience they are arranged alphabetically.

Airglow, also known as light of the night sky and night-sky light, is a faint light that glows permanently in the night sky and is seen most clearly in middle and low latitudes. It is caused by the emission of light from molecules and atoms of oxygen, nitrogen, and sodium (from sea salt) that have absorbed photons from sunlight during the day, raising them to higher energy states from which they fall back at night, emitting photons as they do so.

An anthelion is a spot of bright light that is occasionally seen in the sky at the same altitude as the Sun, but at the opposite AZIMUTH. The phenomenon is

Shadow bands in Asheville, North Carolina, December 1974, colored due to the interception of sunlight by distant clouds or mountain peaks ***(Grant W. Goodge, Historic NWS Collection)***

caused by the REFLECTION and REFRACTION of light by hexagonal ICE PRISMS with vertical axes.

An antitwilight arch is a pink or lilac band that is seen at twilight as an arch rising to about 3° above the horizon at the ANTISOLAR POINT.

Astronomical twilight is the dim daylight that illuminates areas inside the Arctic Circle and Antarctic Circle (*see* AXIAL TILT) during the early and late part of the winter. The Sun is below the horizon, but when it is less than 18° below the horizon the SCATTERING and refraction of light allow some sunlight to reach the surface.

An aureole is a bright, white or pale blue disk, surrounded by a brown ring, that is sometimes seen around the Sun or Moon. A white area with no clearly defined boundary that sometimes surrounds the Sun in a clear sky is also called an aureole.

The aurora comprises lights that are sometimes seen high in the sky in regions close to the North and South Magnetic Poles. Those occurring in the Northern Hemisphere are known as the aurora borealis or northern lights, and those occurring in the Southern Hemisphere as aurora australis or southern lights.

Occasionally, auroras appear in latitudes as low as 40°, but they are most often seen within oval-shaped areas in both hemispheres defined by latitude 67° at midnight and about latitude 76° at midday. These are regions that vary little in their position in relation to the Sun. They are geomagnetic latitudes—measured in relation to the magnetic poles, not the geographic poles—and people within the ovals often see two auroras in the same day, one in the morning and a second the same evening.

The lights may resemble curtains hanging vertically or appear as bands, patches, or arcs of light. Usually the lower part of the display is more clearly defined than the upper part. Auroras are mainly white, but often with parts that are pale green or red and the sky around them may have a greenish tinge. Sometimes the display does not move, but at other times it may undulate gently, like a curtain stirred by a slight draft. Displays may last for several hours, and when they end, the lights move toward the magnetic pole then fade.

Auroras are caused by the interaction of the SOLAR WIND with atoms of OXYGEN and NITROGEN in the upper atmosphere. The solar wind consists of charged particles. When these encounter the Earth's magnetic field they compress it on the daylight side (facing the Sun) and stretch it into a long tail on the nighttime side. Solar-wind protons and electrons from inside the tail are caught and travel along the magnetic field lines. These descend to the surface at the magnetic poles, and the particles descend with them. As they enter the upper atmosphere, the particles start to collide with oxygen and nitrogen atoms. These collisions impart energy to the atoms, raising them to an excited state. Then, as they return to their ground state, the energy they absorbed is released as photons of light. It is this light which causes the auroras.

Aurora australis above the South Pole Station, Antarctica. ***(Commander John Bortniak. NOAA Corps)***

The occurrence of auroras is linked to climate, because the intensity of the solar wind varies with SUNSPOT activity, which in turn is linked to periods of warm or cool climatic conditions (*see* MAUNDER MINIMUM and SPÖRER MINIMUM). During the Maunder minimum between 1645 and 1715, Peter Dass, a Norwegian priest, described many aspects of Norwegian life, but failed to mention auroras, although these would have been clearly visible had they occurred. More recently sunspot activity has increased, reaching a maximum in 1991, and the frequency of auroras has also increased.

A bishop's ring is a faint, reddish-brown corona around the Sun that is caused by the DIFFRACTION of light by DUST particles. The clouds of dust are usually the result of a violent VOLCANIC ERUPTION. Bishop's rings were seen following the eruptions of Krakatau (Krakatoa) in 1883 and Mount Katmai in 1912.

A blue Moon is a meteorological phenomenon in which the Moon appears blue in color. It occurs when the sky contains a large number of particles that are predominantly of one size. The Moon may appear green or orange, but the smaller the particles are the further the color is shifted toward blue. The cause of the coloration is believed to be the diffraction of light between the Moon and the observer. Suitable conditions occasionally follow dust storms, forest fires, or large volcanic eruptions. The Sun also appears blue for the same reason—a blue Sun was seen after the 1883 eruption of Krakatau.

Astronomically, the term *blue Moon* was defined in 1946 in the magazine *Sky and Telescope* as the second full Moon to be seen in a single calendar month. In 1999, *Sky and Telescope* corrected this definition to the third full Moon in a season during which there are four and during a period of 12 sidereal months in which there are 13.

Brocken specter, seen and photographed by Jim Salge looking west from Mount Washington Observatory on September 3, 2004. ***(Mount Washington Observatory)***

Bouguer's halo is a faint, white arc of light, with a radius of about 39°, that is sometimes seen at the antisolar point. It is caused by reflection and refraction and is named after the French scientist Pierre Bouguer (1698–1758), who studied the refraction of light and the effect on light of its passage through the atmosphere.

A Brocken specter is a glory that is sometimes seen in the mist at the summit of the Brocken mountain, a peak in the Harz Mountains, Germany, and on some other mountains. It appears as a gigantic human figure. In fact, it is the shadow of the observer cast on the water droplets in the mist.

A circumhorizontal arc is a brightly colored, horizontal band of light that is seen at an elevation of less than 32° above the horizon when the Sun is a little more than 58° above the horizon. The light is caused by the reflection and refraction of light from ICE CRYSTALS that have vertical axes. The light enters the crystals through their vertical faces and leaves through their horizontal faces. The band of light displays the colors of the spectrum with red at the top.

A circumscribed halo is a halo surrounded by a bright ring. When the Sun is high in the sky, the outer ring touches the edge of the 22° halo at the top and bottom, but is clearly outside it at either side, so it has an approximately elliptical shape. When the Sun is low in the sky, the bottom of the outer ring sags below the halo. This rare phenomenon is caused by the refraction of light through hexagonal ice crystals that have horizontal axes.

A circumzenithed arc is a circular arc, brightly colored with red at the bottom, that is seen more than 58° above the Sun when the Sun is below 32°. It is caused by light rays entering the horizontal tops of hexagonal ice crystals with vertical axes and emerging from vertical sides.

A cloud bow is an arc of light seen in the sky that is caused by the refraction of light through spherical water droplets. It is similar to a fogbow.

A corona is a whitish disk surrounding the Moon or less commonly the Sun. Colors can sometimes be seen, in which case the corona consists of two or more concentric rings that are reddish on the outside and bluish on the inside. The effect is caused by the diffraction of light through the water droplets forming a layer of cloud, commonly altostratus (*see* CLOUD TYPES), between the Sun and the observer. Despite its superficial similarity, a corona is quite different from a halo. If the corona grows

Crepuscular rays seen in February 1975 from Beaucatcher Ridge, Asheville. N.C. ***(Grant W. Goodge. Historic NWS Collection)***

larger over the space of an hour or two, it indicates the water droplets are becoming smaller and the cloud will disperse. If the corona becomes smaller, it means the water droplets are becoming bigger and before long are likely to fall as rain. A corona may also appear in fog. This indicates the fog is thinning and will soon clear.

Crepuscular rays, sometimes called the Sun drawing water, is an optical phenomenon in which what appear to be rays or bands of light radiate upward from the Sun when the Sun is low in the sky. They occur when the sky is partly covered by cloud, leaving gaps through which the Sun shines. If particles of dust or smoke are present in the sky above those gaps, sunlight will be reflected from them. In fact, light shining through the gaps illuminates the particles in its path. *Crepuscular* means "of the twilight" (from the Latin *crepusculum,* "twilight") and crepuscular rays are seen only very early or late in the day. People used to believe the rays were caused by water being drawn from the sky toward the Sun and described the phenomenon as "the Sun drawing water," taking it as a sign of fine weather to come. This is not what is happening, of course, but crepuscular rays can be seen only when there are gaps in the cloud cover and this often means the cloud is breaking up and the weather turning fine.

A dark segment, also called an Earth's shadow, is a dark band that is sometimes seen above the horizon and just below the antitwilight arch. It appears shortly before sunrise or after sunset under conditions of HAZE.

Dayglow is very weak light that is emitted in the mesosphere (*see* ATMOSPHERIC STRUCTURE) and that contributes to daylight. It is caused by the bombardment of oxygen molecules by sunlight in the far ULTRAVIOLET part of the SOLAR SPECTRUM, at wavelengths below 200 nm. Dayglow becomes weaker as the Sun sets.

A dewbow is a very faint rainbow that is sometimes seen in DEW drops on the ground.

A fogbow is a rainbow that is seen in fog. The water droplets that form fog are much smaller than the RAINDROPS that act like prisms to separate white light into its constituent spectral colors, so although they refract light in the same way the rays remain so close to each other that they merge, and the fogbow is white.

Gegenschein is a faint glow that is sometimes seen in the sky opposite the Sun as a circle or ellipse of light. The name is German for "reflection."

A glory is an optical phenomenon in which a shadow cast onto a layer of cloud appears surrounded by one or more circles of light. The light are faintly colored, with the colors of the rainbow and red on the outside of the circle, and if there is more than one circle the innermost one will be the brightest. Glories are caused by the reflection and refraction of light by very small water droplets of fairly uniform size. The Sun, observer, and glory form a straight line, so the glory always surrounds the shadow of the observer. Glories are most often seen by people in aircraft flying above cloud, in which case the glory surrounds the shadow of the airplane, but they also appear to people on the ground. The observer must be looking at a bank of cloud or fog with the Sun behind. The glory will then form around the observer's head, like a halo, and hence the name "glory."

A glory around the shadow of an aircraft on the cloud surface, photographed on October 2, 1970. ***(NOAA/AOML/Hurricane Research Division)***

A green flash, also known as a green ray, is a bright flash of emerald green light that is seen just above the horizon immediately after the Sun has set or immediately before it rises. It lasts for 1–10 seconds or sometimes longer. Light is refracted slightly as it passes through the atmosphere, because of variations in atmospheric density. When the Sun is low in the sky, its light is refracted almost parallel to the surface of the Earth, so the real position of the Sun in the sky is about half a degree lower than its apparent position. Different wavelengths of light are refracted by different amounts. When the Sun is close to the horizon, the atmosphere acts as a prism, breaking sunlight into its constituent colors, with red at the bottom. Sunlight is also scattered, blue being the color most affected. The atmosphere absorbs yellow light. When the red and orange parts of the solar spectrum are just out of sight below the horizon, the remainder of the spectrum is above it. The yellow light is absorbed and the blue light is scattered in all directions. This leaves the green part of the spectrum, which is neither scattered nor absorbed, and so there is a brief flash of brilliantly green light. For a green flash to appear the horizon must be absolutely flat and a long way away, so the effect is most often seen over the sea. The air must be stable (*see* STABILITY OF AIR), because instability causes variations in DENSITY that vary the degree of refraction. Dry air is usually more stable than moist air and so green flashes are seen more often in dry climates than in humid ones.

A halo is a circle of white light surrounding the Sun or Moon. It is seen when the Sun or Moon is behind a layer of cirrostratus cloud, so it appears as a white disk. Most halos have a radius subtending an angle of 22° to the eye of the observer. Less commonly, the radius may subtend an angle of 46°. The halo is caused by the refraction of light through ice crystals in the cloud. The difference in size is due to the path taken by light through the crystals. If light enters through one side of the crystals and exits through another side, it will produce a 22° halo. If it enters through a side and exits through the top or bottom, it will produce a 46° halo. Halos often mean rain is on its way and a halo surrounding the Moon (a ring around the Moon) means rain is likely by morning.

A heavenly cross is a sun pillar crossed by a horizontal bar.

Heiligenschein is an optical phenomenon in which the shadow of an observer on ground covered with vegetation has a bright, white light surrounding the head. It is seen when the Sun is shining and the surface vegetation is covered with dew, provided the dewdrops are of the right size and in the right position to act as lenses, focusing an image of the Sun onto the plant surface beneath. The observer sees this image of the Sun repeated innumerable times and magnified by the dewdrops through which it is seen. *Heiligenschein* is the German for "halo."

Halo over South Pole Station, Antarctica, in January 1979. ***(Commander John Bortniak. NOAA Corps)***

Ice blink is a white gleam that is visible above the horizon when pack ice (*see* SEA ICE) is present in the distance. The gleam is caused by the reflection of light from the ice.

An icebow is an arc of light that resembles a rainbow and is formed in the same way, but by the reflection and refraction of light through ice crystals rather than raindrops. The much smaller size of the crystals does not allow the colors to diverge, so an icebow is always white.

Iridescent cloud is cloud that is partly brightly colored, most often with patches of red and green but sometimes with violet, blue, or yellow. The color is caused by the diffraction of sunlight or moonlight by small water droplets or ice crystals. For iridescence (also called irisation) to occur the particles must be of approximately uniform size and the cloud must be in the same part of the sky as the Sun or Moon. Iridescent clouds are most often seen when the Sun or Moon is behind cloud or some barrier; when it is in full view its light is so intense as to make the colors invisible. Which colors are seen depends on the size of the droplets or crystals and the angle between the Sun, cloud, and observer.

Iridescence, or irisation, is the appearance of colors around the edges of clouds. It is caused by the diffraction of sunlight by supercooled (*see* SUPERCOOLING) water droplets or ICE CRYSTALS. The colors that are produced vary according to the size of the droplets and the angular distance from the Sun. For the phenomenon to occur the cloud must be in the same part of the sky as the Sun and it is often seen at its best when the Sun is behind the cloud. Irisation often occurs with altocumulus.

Land blink is a yellow glow that is seen in polar regions over an extensive snow-covered surface.

Land sky is the dark color of the underside of a cloud that is seen in polar regions over a land surface that is free from snow. The cloud appears relatively dark because its base is not illuminated by light reflected from a snow-covered surface, but it is not so dark as a water sky.

Loom is a glow of light just below the horizon that is caused by the refraction of light passing from cooler air aloft to warmer air below. It is a type of mirage that does not involve an image of a physical object.

A luminous meteor is any atmospheric phenomenon that appears as a pattern of light in the sky. Luminous meteors include aurorae, coronas, halos, fogbows, rainbows, and similar phenomena, but not LIGHTNING, which is excluded.

A moon pillar is a column of light that occasionally appears above or below the Moon, when the Moon is low in the sky. It is the nighttime equivalent of a sun pillar and forms under similar conditions, by the reflection of moonlight by the undersides of slowly falling ice crystals of the types known as plates and capped columns.

Nightglow results from radiation that is emitted at night in the mesosphere, mainly at heights of 50–60 miles (80–100 km). It is due to chemical reactions among the constituents of the air at that height and it becomes stronger as the night progresses. Atomic oxygen emits yellow-green light, at a wavelength (*see* WAVE CHARACTERISTICS) of 555.7 nm, sodium emits yellow light at 589 nm, and HYDROXYL and oxygen molecules emit radiation at wavelengths outside the visible spectrum. Even the visible light is too faint to be visible from the ground, although instruments on satellites can detect it.

A rainbow is an arch of colored bands that is the most familiar of all optical weather phenomena. The colors are those of the spectrum—the colors that combine to make white light and into which white light can be broken by passing it through a prism. Not all the colors are visible in every rainbow, but when they are they consist of violet, indigo, blue, green, yellow, orange, and red, with violet on the inside of the arch and red on the outside. Sometimes a secondary rainbow can be seen elevated about 8° above the primary, and brightest, bow. The order of colors is reversed in the secondary bow.

A rainbow occurs when the Sun is behind the observer and is less than 42° above the horizon, and rain is falling in front at the same time. The observer sees sunlight that is reflected from the inside of the rear surface of raindrops, but that is also refracted twice, first as it enters each raindrop and again as it leaves. As light passes from air to the water of the raindrop, its speed is slowed, but different wavelengths are slowed by different amounts. The violet wavelength is slowed most, red light is slowed least, and the colors between are slowed by intermediate amounts. The effect is to separate the colors. The angle between the sunlight striking the raindrops and the rainbow arch is 42° for red, on the outside of the arch, and 40° for violet, on the inside of the arch, with the other colors between.

Light from the rainbow approaches the observer at an angle of 40–42° to the angle of the Sun's rays. If the Sun is more than 42° above the horizon, the red band at the top of the rainbow will be below ground level and there will be no rainbow. The lower the Sun, the higher the rainbow arc will be. From aircraft, a rainbow can sometimes be seen as a full circle, but it can never appear as more than a semicircle to an observer at ground level.

A secondary rainbow forms when light is reflected twice inside each raindrop. This increases to about 50° the angle by which red light is refracted and the second reflection reverses the order of colors. Consequently, the secondary rainbow is seen about 8° above the primary, with red on the inside. Very occasionally, a third or even fourth bow occurs, but usually these are too faint to be visible. Each additional bow results from an additional reflection inside the raindrops, and each reflection reverses the order of the colors.

A sky map is a pattern of light and dark areas that is sometimes seen on the underside of a cloud layer, most commonly in high latitudes when the surface is partly covered by snow or ice. The pattern is made by the different amounts of light reflected from the different types of surface and so it can resemble the surface, like a map.

Snow blink, also called snow sky, is the bright, glaring appearance of the underside of clouds when the ground is covered with snow. It is caused by the illumination of the cloud base by light reflected from the snow.

A subsun is a bright spot of light that is seen on the top of a layer of cloud by an observer who is flying in an aircraft or standing high on a mountain. The light is caused by the reflection of sunlight from the horizontal upper surfaces of ice crystals at the top of the cloud.

A sun cross is a rare optical phenomenon that consists of a vertical band of white light in the sky with a horizontal band across it. It is seen when a sun pillar and sun dog both appear at the same time and part of the circle of the sun dog intersects the sun pillar.

A sun dog, also known as a mock sun or parhelion, is a bright patch that is sometimes seen to one side of the Sun, and usually slightly below it. It is caused by the refraction of light by ice crystals and occurs when ice crystals are falling very slowly. Sun dogs are usually associated with a 22° halo, in which case they occur as

Parhelion or sun dogs, with a halo, at South Pole Station, Antarctica, in January 1979. ***(Commander John Bortniak. NOAA Corps)***

Sun pillar projected onto altocumulus seen from Flat Top Mountain, North Carolina, February 10, 1979 ***(Grant W. Goodge Historic NWS Collection)***

a pair, one to either side of the halo, but they can also occur singly. Moon dogs, or mock moons, form in the same way, but are less common.

A sun pillar is an optical phenomenon in which a bright shaft of light extends upward from the Sun. A pillar may also extend below the Sun, but this is much rarer. It is caused by the reflection of light from the undersides of ice crystals of the types known as plates and capped columns, when these are falling very slowly.

A supernumerary bow is a rainbow that appears inside the primary bow with the colors in the same order as those in the primary (the secondary and occasionally tertiary bows appear on the outside of the primary with the colors reversed in the secondary). It is seen when the water droplets are very small. Supernumerary bows are often superimposed on the primary bow. They may broaden particular bands or cause them to disappear. If the droplets are smaller than about 0.004 inch (0.1 mm) in diameter, the superposition of colors may produce a rainbow with pale colors at the edges but an almost white central band. These droplets are similar in size to those of fine drizzle and the bow they produce is similar to a fogbow. It is sometimes called Ulloa's ring.

A water sky describes the appearance of a cloudy sky over water, when the Sun is high and the ALBEDO of the water is low. Little light is reflected to illuminate the base of the cloud, which is consequently dark in color.

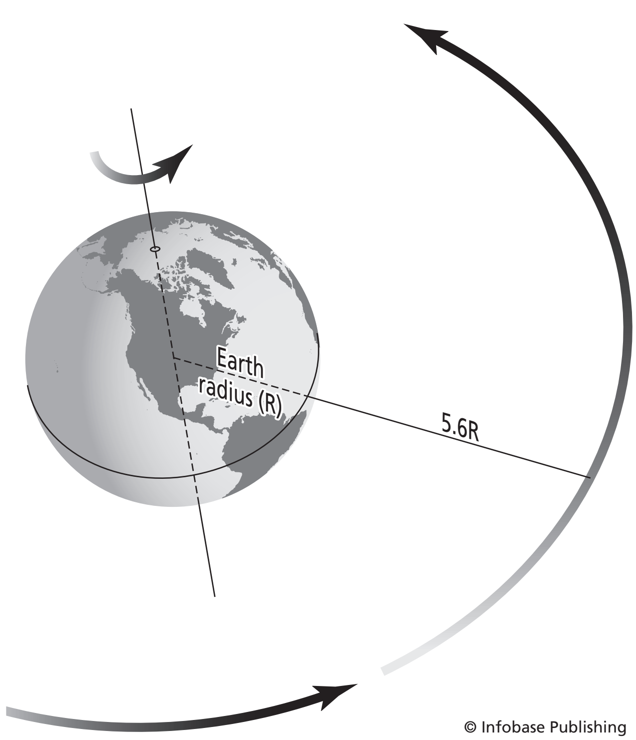
A white horizontal arc is an arc that is seen when sunshine falls onto a cloud that consists of ice crystals with both vertical and horizontal faces. The faces act as mirrors. The arc passes through the shadow of the observer, which is cast onto the cloud. The phenomenon is very rare.

Zodiacal light is a band of light that appears in the sky at night, in the east shortly before dawn or in the west shortly after sunset. It is believed to be caused by the diffraction and reflection of light by dust particles in the upper atmosphere and in space beyond along the PLANE OF THE ECLIPTIC. It is most often seen in the TROPICS, where the ecliptic is almost vertically overhead.

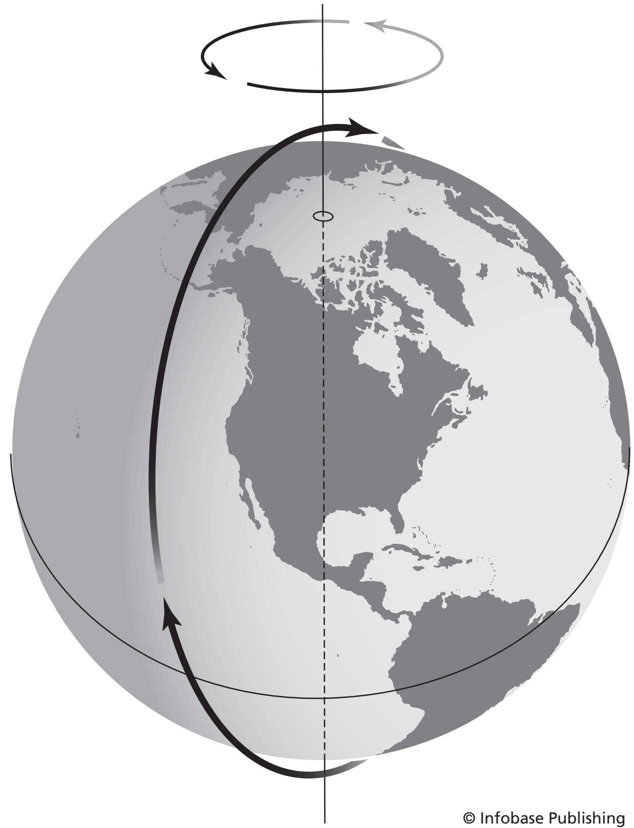
orbit The path that a particle or body follows around a central point or mass. As waves move across the sea or a lake, individual water particles move up and forward and down and to the rear in approximately circular vertical orbits. The path the Earth follows around the Sun is its orbit, as are the paths satellites follow around the Earth or other large bodies. WEATHER SATELLITES are placed in either geostationary orbits or in polar orbits.

A geostationary orbit, also known as a geosynchronous orbit or Clarke orbit, is a satellite orbit at a height of about 22,370 miles (36,000 km), which is about 5.6 times the radius of the Earth, in which the satellite travels in the same direction as the Earth's rotation. At this height, the satellite completes a single orbit in precisely one sidereal day (a DAY measured with reference to the fixed stars). This means that the satellite remains permanently above the same point on the equator. Its field of view is almost an entire hemisphere. The satellite takes 20 minutes to complete a scan of its field of view and provides images with a resolution nearly as good as those from satellites in much lower polar orbit. The writer Sir Arthur C. Clarke first suggested the possibility of placing satellites into geostationary orbit, and the orbit is sometimes named after him.

A satellite in a polar orbit passes close to the North and South Poles at an altitude of about 560 miles (900 km), which is one-seventh the radius of the Earth. A polar orbit may be fixed in relation to the position of



A satellite in geostationary orbit moves at the same rate as the Earth rotates, so it remains permanently above one point on the surface.



A satellite in polar orbit passes close to or across the North and South Poles.

the Sun (Sun-synchronous orbit), but making an angle with the meridians, so the entire surface of the Earth is scanned in successive passes. A satellite in a sun-synchronous orbit passes close to the poles, but at an angle to the meridians (lines of longitude), and takes about 100 minutes to complete one orbit. The satellite crosses the equator about 15 times each day and passes over every part of the surface of the Earth at the same time each day.

An inclined orbit is an orbit that falls between the geostationary and polar orbits. A geostationary orbit has an inclination of 0° and a polar orbit an inclination of 90°. The angle of inclination for the orbit is chosen to allow the greatest observation to be of a particular region of interest, but because an inclined orbit is not Sun-synchronous, that area will be observed at a different time each day.

Inclination is the angle between the orbital plane of a body and a reference plane centered on the body about which it is orbiting. In the case of the Earth, the reference plane is the PLANE OF THE ECLIPTIC. In the case of satellites it is the equatorial plane of the planet about which they orbit. The angle between the rotational axis of a body and its orbital plane is also known as the inclination.

The time it takes for an orbiting body to complete one full journey around its orbital path is known as its orbit period. The orbit period is measured as the time that elapses between two successive passes of a fixed point. The Earth's orbit around the Sun has a period of one year, but the length of the year varies according to the way it is measured. A calendar year contains 365 days, with a leap year of 366 days in every fourth year. (Century years are leap years only if the first two digits are exactly divisible by 4; 1900 was not a leap year, 2000 was, and 2100 will not be). A year counted from the interval between EQUINOXES, called a tropical year, contains 365.242 days. A sidereal year, measured by the positions of the fixed stars, has 365.256 days. An eclipse year, measured as the time that elapses between successive passages of the Sun through the points where the orbits of Earth and the Moon intersect (called the Moon's nodes) has 346.620 days. A Gaussian year, measured with reference to the semimajor (smaller) of the two axes in the elliptical orbital path, has 365.257 days.

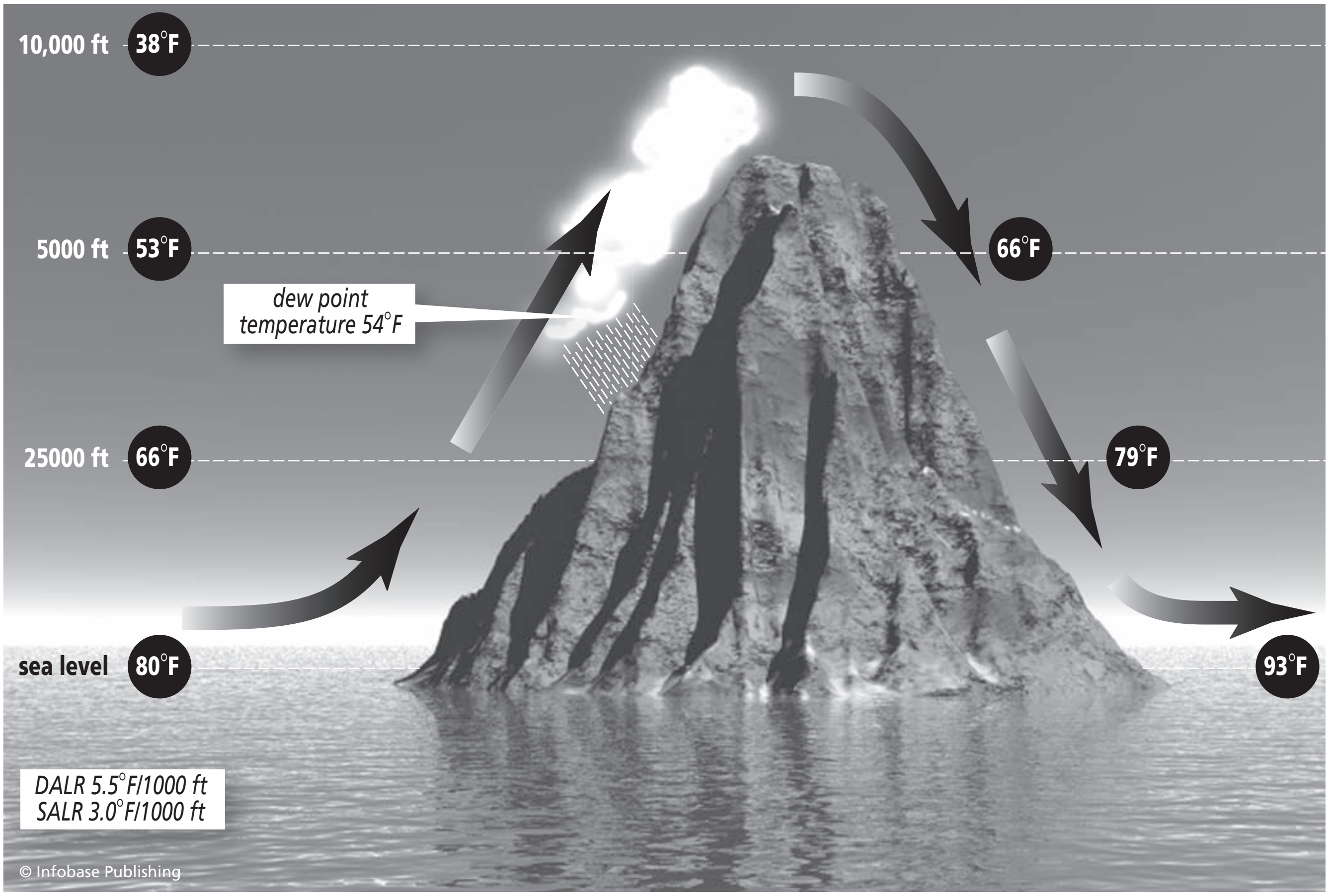
Ordovician The middle period of the Paleozoic era of Earth history that began 488.3 million years ago and ended 443.7 million years ago. A map of the Ordovician world would have looked very different from a modern map. Southern Europe, Africa, Australia, and South America were joined together as the supercontinent Gondwanaland, which straddled the South Pole. North America was at the equator, tilted about 45° from its present orientation and colliding with a microcontinent called Baltica. Europe apart from southern Europe was in the Southern Hemisphere Tropics.

Extensive shallow seas supported abundant marine life and climates were mild for most of the period, but near the end of the Ordovician there was an intense GLACIAL PERIOD. GLACIERS were widespread in Gondwanaland—at the South Pole—and there were glaciers in what is now the Sahara. Conditions were so harsh that approximately 60 percent of all animal species became extinct. The cause of the ice age is unknown. Certainly it was not linked to low levels of atmospheric CARBON DIOXIDE (*see* GREENHOUSE EFFECT); these were 8–20 times higher than the present concentration. (*See* APPENDIX V: GEOLOGIC TIMESCALE.)

orographic Pertaining to mountains, and especially to their location and form. The word is derived from the Greek *oros,* meaning "mountain," and *graph* , which means "writing."

When mountains or a mountain range lie in the path of moving air, the air must rise to cross the obstruction. This forced raising of air is called orographic lifting. The effects are most pronounced when air crosses a mountain range lying at right angles across its path. The Rocky Mountains are a good example. They are high and aligned north and south, and the prevailing air movement is from west to east. Air is constantly being forced to cross the mountains, and this produces marked differences in the climates to the west and the east of them.

Orographic lifting has several effects. The first is to increase PRECIPITATION on the windward slope. As air rises it expands and cools adiabatically (*see* ADIABAT). Unless it was already saturated, the air temperature decreases with height at the dry adiabatic LAPSE RATE (if the air is saturated its temperature falls at the saturated adiabatic lapse rate). The amount of water vapor that air can hold varies with the air temperature. Therefore, as the air temperature falls the relative HUMIDITY rises. When the rising air reaches the lifting CONDENSATION level water vapor will start to condense and cloud



As air rises to cross the mountain, it cools at the dry adiabatic lapse rate (DALR) until it reaches its dew point temperature. Cloud then forms and rain falls. The air continues cooling at the saturated adiabatic lapse rate (SALR). On the lee side of the summit, the subsiding air warms at the DALR, reaching sea level much warmer and drier than it was at sea level on the windward side.

will form. Whether cloud forms and, if it does, whether it produces precipitation will depend on the original humidity of the air. Air that has crossed the ocean, such as the air reaching the Rockies from the west, will carry a large amount of moisture. Consequently, orographic lifting will usually produce cloud and precipitation. A mountain range located deep in the interior of a continent will have a much smaller effect, because the air reaching it is drier.

Tamarack, California, on the windward slopes of Mount Whitney, has the heaviest average snowfall in North America, with 37.5 feet (11.4 m) a year; in January 1911, 32.5 feet (9.9 m) fell in one month. Other places sometimes receive more in a single season, however. In the winter of 1998–99, for example, 95 feet (29 m) of snow fell on Mount Baker, in Washington State. The people of Lloro, Colombia, probably experience the highest average rainfall in the world. Lloro, on the windward slopes of the Andes at an elevation of 520 feet (159 m), is estimated to have received 523.6 inches (13,300 mm) of rain a year over 29 years. Cherrapunji, at an elevation of 4,309 feet (1,313 m) in the mountains of northeastern India, receives the rainfall resulting from the orographic lifting of MONSOON winds. Its average annual rainfall is 425 inches (10,800 mm), but between August 1860 and July 1861 Cherrapunji received 1,041 inches (26,441 mm), which is approximately 86 feet (26 m) of rain.

The increase in precipitation that occurs over the land or sea that lies on the upwind side of a range of hills or mountains is called the upwind effect. It occurs because air moving toward the orographic barrier rises before it reaches the solid surface. Consequently, air is cooling and its relative humidity is increasing for some distance upwind of the barrier. Rain that falls on the windward slope of a hill or mountain as a direct consequence of orographic lifting is known as orographic rain. The amount of orographic rain is equal to the difference between the total amount of rain that fell due to a particular weather system and the amount of rain that system would have been estimated to produce over level ground.

Precipitation falls heavily on the windward side of the mountains, but the LEE side is dry, sometimes extremely dry. It lies in a rain shadow. Death Valley, California, lies in a rain shadow. It receives an average 1.6 inches (41 mm) of rain a year.

Rising, unsaturated air cools at the dry adiabatic lapse rate (DALR) of 5.5°F per 1,000 feet (10°C/km). Suppose the air starts at a sea-level temperature of 80°F (27°C) and that the DEW point temperature is 54°F (12°C). The lifting condensation level, at which the air temperature falls to the dew point temperature, will be at about 4,700 feet (1,430 m). WATER VAPOR will then start condensing and, because of the release of LATENT HEAT, the air will continue cooling at the saturated adiabatic lapse rate (SALR) of 3°F per 1,000 feet (5.5°C/km). By the time it crosses the mountain peak, say at 10,000 feet (3,000 m), the air temperature will be 38°F (3.3°C).

The air at the top of the mountain is saturated, water vapor is still condensing from it, and the mountain peak is shrouded in cloud. Because its relative humidity (RH) is 100 percent, the dew point temperature and the actual air temperature must be the same. The dew point temperature at the mountaintop is therefore 38°F (3.3°C). Air now starts descending on the lee side of the mountain. As it does so, it is compressed and its temperature rises. It immediately rises above the dew point temperature, so its RH falls below saturation. Water vapor ceases to condense, and the sinking air warms at the DALR. By the time it is once more at sea level, its temperature has risen to 93°F (34°C) and it is extremely dry. This is why there is often a dry DESERT in the rain shadow on the lee side of a large mountain range.

It can also happen that air on the windward side of the mountain forms a pool that is partly trapped. Air at a higher level flows over the top of the pool and down the lee side. This causes a wind of the FÖHN type.

Hills and mountains are often windy places. This is another consequence of orographic lifting. The rising air pushes against the air above the mountain. This causes a series of vertical air movements that continue downwind from the peak. One consequence is that the wind speed is greatly reduced on the lower part of the slope on both sides of the barrier, but greatly increased at the summit by the VENTURI EFFECT.

Orosirian The third of the four periods of the Paleoproterozoic era of Earth history, which began 2,050 million years ago and ended 1,800 million years ago. Earth suffered the two largest known asteroid impacts during the Orosirian, one about 2,023 million years ago and the other about 1,850 million years ago.

The name Orosirian is derived from *orosira,* the Greek word for "mountain range," referring to the fact that during the Orosirian crustal movements (*see* PLATE TECTONICS) were raising mountain ranges on most continents. It was probably during the Orosirian that the atmosphere accumulated sufficient oxygen to become oxidizing, rather than reducing. *See* APPENDIX V: GEOLOGIC TIMESCALE.

osmosis The process in which water molecules cross a membrane that is permeable to them and that separates two solutions of different concentrations. The molecules move from the solution of weaker concentration to the one of higher concentration. This dilutes the stronger solution by the addition of water and strengthens the weaker solution by the removal of water. Water continues to cross the membrane until the concentrations of the two solutions are equal. The stronger solution is said to be hyperosmotic with respect to the weaker solution, and the weaker solution is said to be hypoosmotic with respect to the stronger solution. Solutions of equal concentration are said to be isoosmotic. The membrane is said to be selectively permeable.

Osmosis occurs regardless of the composition of the two solutions. It is only their relative concentrations which matters. Water will flow by osmosis from seawater to a very concentrated sugar solution, because the seawater contains a lower concentration of solute molecules than does the sugar solution.

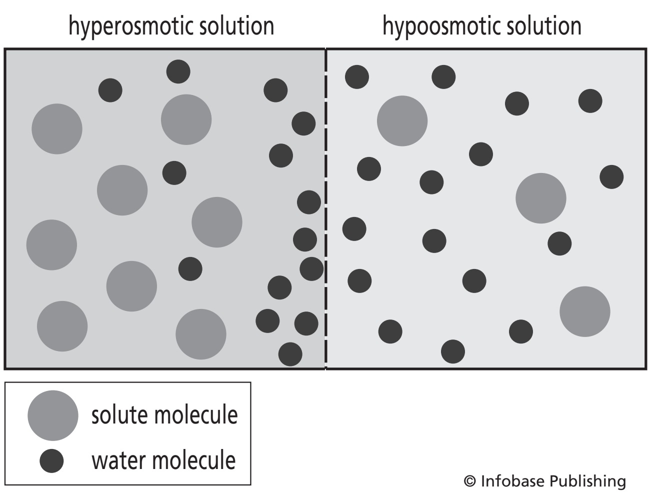
Osmosis exerts a pressure across the selectively permeable membrane. The osmotic pressure of a solution is directly proportional to its solute concentration, and it can be measured by an osmometer. In one type of osmometer, the specimen solution is contained in one section of a tube and separated by a selectively permeable membrane from distilled water in the other part of the tube. Osmosis will cause water to flow into the solution, thereby increasing its volume. A piston exerts a pressure that is sufficient to prevent this expansion and therefore to prevent water from crossing the membrane. The osmotic pressure is the pressure the piston needs to exert in order to maintain a constant volume in the solution.

Living cells can be damaged by the osmosis that occurs if the concentration of the internal and external solutions changes radically. Plant cells have walls that make them less susceptible to damage of this kind than animal cells, which lack walls. If a freshwater organism is immersed in seawater, so the seawater fills the intercellular spaces, water will move out of cells under osmotic pressure. This will cause cell dehydration. If a marine organism is immersed in freshwater, the reverse happens. Water flows into cells under osmotic pressure. This can cause animal cells to lyse (burst). Plant cells become turgid (rigid).

Freezing also causes injury by osmosis. When ice crystals form in the intercellular solution, its concentration increases due to the removal of water. This causes water to flow out of the adjacent cells, with consequent dehydration.

Osmosis is exploited industrially to remove salt from water that is too salty for drinking. Two processes are used: reverse osmosis and electrodialysis. In reverse osmosis, salt water is brought against a selectively permeable membrane under a pressure that exceeds the osmotic pressure of the solution. Water flows across the membrane from the salt water.

In electrodialysis two membranes are used and an electric current is passed through the solution. Common salt (NaCl) separates in solution into sodium ions, carrying a positive charge (Na^+) and chlorine ions carrying a negative charge (Cl^-). The electric current causes N^+ ions to move across one membrane and Cl^- ions to move across the other, leaving pure water in the area between the membranes. This technique is used to treat only brackish water, not seawater.



A selectively permeable membrane separates two solutions of unequal concentration. Water molecules flow across the membrane from the hypoosmotic solution to the hyperosmotic solution. They continue to do so until the proportion of solute to water molecules (solvent) is the same on both sides of the membrane.

oxygen (O) Oxygen is the most abundant element in the Earth's crust, where it occurs combined with other elements (such as aluminum, carbon, iron, and sulfur) in the minerals from which rocks are composed, as well as in water. By weight, crustal rocks are 47 percent oxygen and the oceans are 88.8 percent oxygen.

Oxygen has an atomic number of 8 and relative atomic mass of 15.9994. It melts at -353.92°F (-214.4°C) and boils at -297.4°F (-183°C). It occurs in the atmosphere as a colorless, odorless gas (but pale blue as a liquid) comprising 20.946 percent of the atmosphere by volume, with a concentration of 209,460 parts per million. In its commonest form, oxygen atoms bond in pairs as diatomic oxygen (O_2), but atoms can also bond in threes to form OZONE (O_3).

Oxygen is extremely reactive, and many oxidation reactions release energy. Aerobic RESPIRATION releases energy from oxidation reactions, and COMBUSTION releases heat through chain reactions in which carbon and hydrogen are oxidized. Oxygen is slightly soluble in water, and aquatic aerobic organisms, such as fish, use dissolved oxygen for respiration.

Oxygen occurs in several ISOTOPES. Natural oxygen is mainly oxygen-16, usually written ^{16}O, in which the atomic nucleus contains 8 protons and 8 neutrons. This is the most abundant isotope, with a relative atomic mass of 15.9994 which is approximately 16, and it accounts for 99.76 percent of natural oxygen. The addition of one more neutron produces ^{17}O, accounting for 0.04 percent of natural oxygen, and adding two more neutrons produces ^{18}O, accounting for 0.20 percent of natural oxygen. There are also three, very short-lived, radioactive isotopes, ^{14}O, ^{15}O, and ^{19}O.

Information about past climates can be inferred from studies of the two most important isotopes, ^{16}O and ^{18}O. These occur in atmospheric oxygen in the ratio of about one part of ^{18}O to 499 parts of ^{16}O. Both isotopes bond equally well with HYDROGEN to form water, so for every 499 $H_2{}^{16}O$ water molecules there is 1 molecule of $H_2{}^{18}O$. Chemically, the two are identical, but the $H_2{}^{18}O$ is slightly the heavier. Because $H_2{}^{16}O$ is lighter, it evaporates more readily than $H_2{}^{18}O$. Less energy is needed for molecules of $H_2{}^{16}O$ to break free from the liquid surface. Once in the air, gaseous water molecules condense to form liquid droplets, containing a higher proportion of the lighter isotope. The droplets fall to the surface once more as PRECIPITATION, so the relative proportions of the two isotopes remain constant in seawater.

During the onset of a GLACIAL PERIOD, however, SNOW falling over the expanding ice sheets remains there. The ice sheets grow thicker, the snow is compacted into ice, and an increasing proportion of the world's water is removed from the oceans and stored on land. The snow is made from water containing more than 499 parts of ^{16}O to every one part ^{18}O, and since the water molecules evaporated primarily from the oceans, as ^{16}O is removed the proportion of ^{18}O in seawater increases.

Small animals called foraminifera, or forams, are abundant in the oceans. They are tiny, most of them less than 0.04 inch (1 mm) in diameter, but they live inside shells they make for themselves, and they have existed for at least the last 600 million years. Their shells are made from calcium carbonate ($CaCO_3$), which they synthesize from the water around them. The oxygen they use contains the two isotopes in the same proportion as is present in the water.

When forams die, the soft parts of their bodies decompose and vanish, but their insoluble shells sink to the bottom of shallow water (at below about 2–3 miles; 3–5 km, called the carbonate compensation depth, $CaCO_3$ dissolves once more). There they form part of the sediment that eventually becomes sedimentary rock. Those rocks contain oxygen with a ratio of the ^{16}O and ^{18}O isotopes that records the ratio in the oceans at the time the $CaCO_3$ was made.

If the $CaCO_3$ is enriched in ^{18}O it indicates that ^{16}O was accumulating in snow and ice at the time and therefore that the ice sheets were expanding as the climate grew colder. The $CaCO_3$ can be dated, for example by RADIOCARBON DATING, and so changes over time in the ratio of the oxygen isotopes can be interpreted as changes in the global climate.

Similarly, the isotope ratio is preserved in the ice sheets themselves. There they reflect changes in temperature. All the water molecules are enriched with ^{16}O, but by an amount that depends on the temperature. Although ^{16}O evaporates more readily than ^{18}O, ^{18}O also evaporates, and the warmer the weather the more it is able to do so. Consequently, an increase in the proportion of ^{18}O in the ice indicates warmer weather, a decrease indicates colder weather, and this "thermometer" is so sensitive it can be used to detect the difference between winter and summer temperatures, which is a help in counting the annual layers in ICE CORES.

Analysis of these two oxygen isotopes is a major tool in the reconstruction of the history of the global climate.

ozone A form of oxygen in which the molecule comprises three atoms (O_3) rather than the two of ordinary oxygen (O_2). Ozone is a pale blue gas and a powerful oxidizing agent. In the troposphere (*see* ATMOSPHERIC STRUCTURE) it forms by a series of reactions in which ULTRAVIOLET (UV) RADIATION reduces nitrogen dioxide (NO_2) to nitrous oxide (NO), releasing one oxygen atom (O), which reacts with oxygen (O_2) to form O_3:

$$NO_2 + UV \rightarrow NO + O$$

$$O + O_2 \rightarrow O_3$$

Ozone is involved in the formation of PHOTOCHEMICAL SMOG, can damage crops and other vegetation, and can accelerate the deterioration of rubber and other materials. It is also harmful to human health, some people being sensitive to ozone at concentrations of as little as 0.001 ppm. In many people, a concentration of 0.15 ppm causes irritation of the respiratory tract with associated discomfort, and at 0.17 ppm persons with asthma and other respiratory ailments are seriously affected. In most countries, standards that are set for air quality aim to limit human exposure to ozone. In the stratosphere, ozone absorbs UV radiation. *See* OZONE LAYER.

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Kurchella, Charles E., and Margaret C. Hyland. *Environmental Science*. 2nd ed. Boston: Allyn and Bacon, 1986.

ozone layer **(ozonosphere)** A region of the stratosphere (*see* ATMOSPHERIC STRUCTURE) between 20 km and 30 km (66,000–98,000 feet) above sea level where the concentration of OZONE (O_3) is usually higher than it is elsewhere, commonly reaching 10^{18}–10^{19} molecules per cubic meter, or 220–460 Dobson units (DU, *see* UNITS OF MEASUREMENT). The ozone forms in a two-step reaction. In the first step, a molecule of oxygen (O_2) absorbs a photon of ULTRAVIOLET RADIATION (UV), having a wavelength of 240 nanometers (nm) and 5.16 electron volts (eV) of energy. This energy is sufficient to break the bond between the two oxygen atoms, to form two single atoms. Some of these atoms then collide with oxygen molecules in the presence of a molecule of any other substance. The additional molecule is needed to absorb momentum from the oxygen atom and molecule, thus allowing them to bond together. The two steps in the reaction are:

$$O_2 + \textit{photon} \rightarrow O + O \qquad (1)$$

$$O_2 + O + M \rightarrow O_3 + M \qquad (2)$$

where the photon supplies the energy and M is the molecule of any other substance (usually nitrogen, N_2).

The short-wave UV radiation that dissociates oxygen molecules is known as “hard” UV or UV-C. “Soft” UV, or UV-B, has a longer wavelength. UV with a wavelength that includes some UV-C but more UV-B is absorbed by ozone and causes it to dissociate. This reaction is:

$$O_3 + \textit{photon} \rightarrow O_2 + O \qquad (3)$$

Ozone is also destroyed by reacting with single oxygen atoms:

$$O_3 + O \rightarrow 2O_2 \qquad (4)$$

Reaction 1, in which oxygen molecules absorb UV radiation, occurs most strongly at very high altitudes above 50 miles (80 km), which is the height at which the density of the atmosphere is such as to cause a substantial proportion of the incoming UV-C to strike oxygen molecules. Ozone formation, by reaction 2, requires the collision of three molecules, and this is most likely to occur at much lower altitudes, in the denser air where molecular collisions are frequent. Air movements in the stratosphere cause enough mixing for some atomic oxygen to be carried to lower levels where they can engage in reaction 2. Ozone levels are then maintained by reactions 2 and 3, with atomic oxygen being fed constantly from above. This balance results in the highest concentration of ozone occurring at about 30 km (19 miles) over the equator and about 18 km (11 miles) over the North and South Poles.

Reactions 1 and 3 depend on sunlight, so they cease at night, while reactions 2 and 4 continue. Reactions 1 and 3 proceed most strongly in low latitudes, because that is where solar radiation is most intense. Ozone does not accumulate over the TROPICS or disappear in winter from the polar stratosphere, because air currents at high level transport stratospheric ozone away from the equator and toward the poles, constantly replenishing the supply.

In 1985, research by three British scientists, J. C. Farman, B. G. Gardiner, and J. D. Shanklin, revealed that the seasonal decrease in the concentration of stratospheric ozone over central Antarctica had become greater than it had been in previous years. Their ground-based observation was quickly confirmed by examining satellite measurements. The decrease occurs naturally in latitudes above 60°S during late winter and early spring, from September to December, and its extent varies from year to year, but the studies indicated that some new factor had become involved. Further research found the depletion of ozone was caused by halons (chemicals containing bromine) used in fire extinguishers, but mainly by CFCs.

The region in which the stratospheric ozone concentration is reduced in late winter and early spring came to be known as the “ozone hole.” There is always some ozone present, so there is not literally a “hole”, but in some years levels have fallen well below their usual values, to only a little more than 100 DU. In October 1993, the level fell to its lowest value, of 91 DU (due partly to sulfate particles released from the eruption of Mount Pinatubo). Stratospheric ozone depletion occurs within the POLAR STRATOSPHERIC CLOUDS that form inside the polar VORTEX.

Reaction to the discovery of severe ozone depletion led to international discussions culminating in the Montreal Protocol on Substances That Deplete the Ozone Layer (*see* APPENDIX IV: LAWS, REGULATIONS, AND INTERNATIONAL AGREEMENTS). Implementation of the measures listed in the Montreal Protocol has checked the depletion of the ozone layer and in time ozone levels are expected to recover.

A halogen is a chemical element that belongs to Group VII of the periodic table. The halogens are fluo-

Ozone depletion potential

Compound	Lifetime (years)	Ozone depletion potential
CFC-11	75	1.0
CFC-12	111	1.0
CFC-113	90	0.8
CFC-114	185	1.0
CFC-115	380	0.6
HCFC-22	20	0.05
Methyl chloroform	6.5	0.10
Carbon tetrachloride	50	1.06
Halon-1211	25	3.0
Halon-1301	110	10.0
Halon-2402	not known	6.0

rine, chlorine, bromine, iodine, and astatine. When halogens enter the stratosphere they are able to engage in chemical reactions that deplete the ozone layer. Halogens are emitted naturally during VOLCANIC ERUPTIONS and the amount and intensity of volcanic activity partly determines the amount of ozone present in the stratosphere. Certain halogens are also used in industrially manufactured compounds. Chlorine and fluorine are used in chlorofluorocarbons (*see* CFCs) and chlorine, fluorine, and bromine are used in halons. CFCs and halons are implicated in the depletion of the ozone layer and their use is being phased out.

Halon is the commercial name for one of the bromofluorocarbons, which are chemical compounds that are used in fire extinguishers. Halon-1211 is a compound of carbon, chlorine, fluorine, and bromine ($CClF_2Br$) that is used in portable fire extinguishers. Halon-1301 is a compound of carbon, fluorine, and bromine (CF_3Br) and is used in fire extinguishers that are installed in fixed positions and work by flooding the area adjacent to them. Once it is released into the atmosphere, halon-1211 survives for 25 years before being removed by natural processes and halon-1301 survives for 110 years. When halons reach the stratosphere, they are broken down by exposure to ultraviolet radiation and then engage in a series of reactions that deplete the ozone layer. Halon-1211 has an ozone depletion potential of 3.0 and that of halon-1301 is 10.0.

Ozone depletion potential is a measure of the extent to which a particular chemical compound is likely to remove ozone from the ozone layer, compared with the extent to which CFC-11 (Freon-11) does so. CFC-11 is given a value of 1 and other compounds are evaluated on this scale. As well as CFCs, the list of compounds implicated in ozone depletion include hydrofluorocarbons (HCFCs) and halons, which are compounds containing bromine. The table (above, left) lists the compounds most strongly implicated in stratospheric ozone depletion, with their atmospheric lifetimes and ozone depletion potential values.

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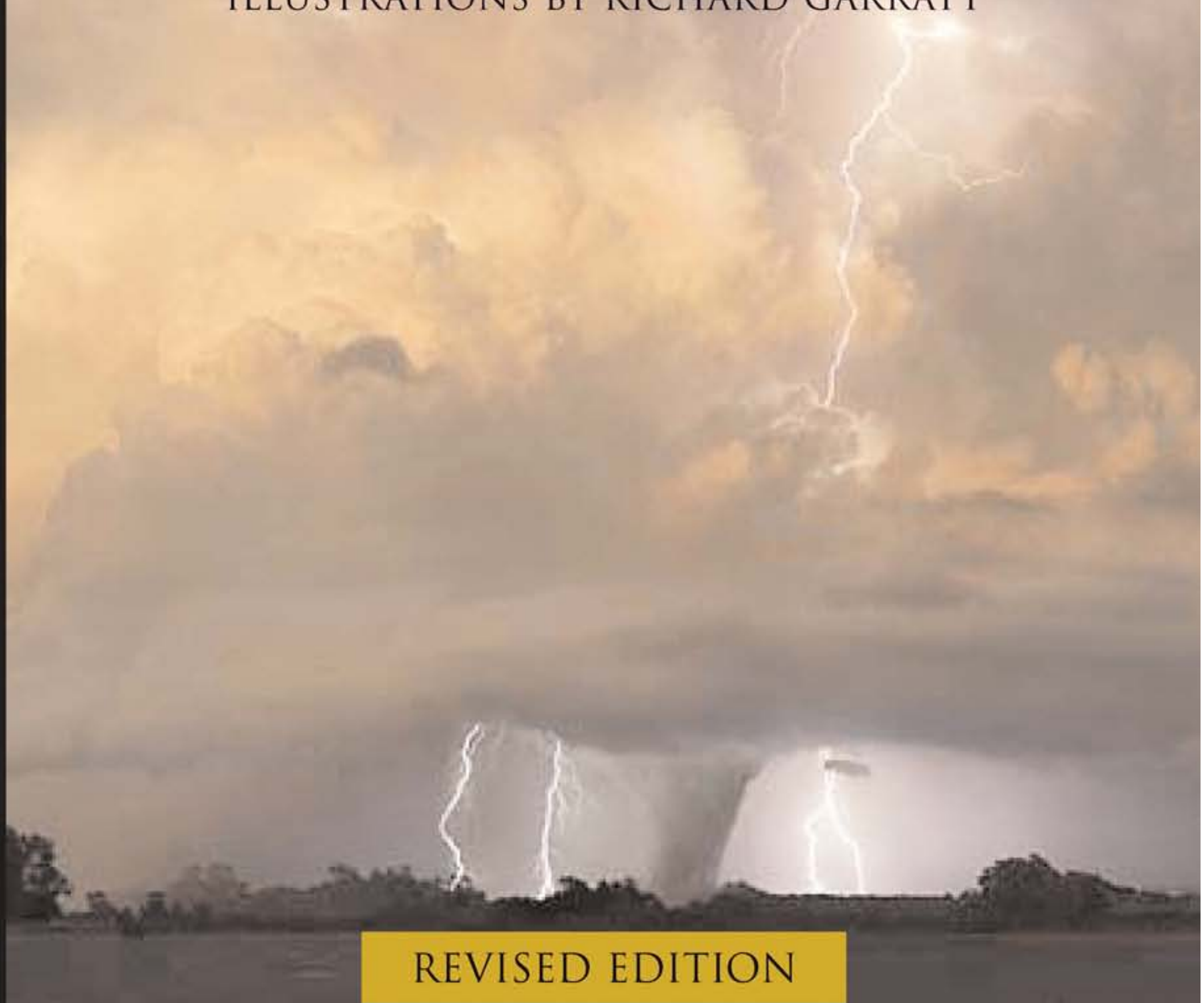

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Contents

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P

Pacific- and Indian-Ocean Common Water (PIOCW) The deep waters of the Pacific and Indian Oceans, which are usually considered together, as a single mass of water. Their characteristics are very similar. Both have a temperature of 35.3°F (1.5°C) and a salinity of 34.7 per mil.

Pacific Decadal Oscillation (PDO) A change that occurs over a period of several decades in the ocean-atmosphere system in the Pacific basin. It affects the temperature of the lower atmosphere, passing through alternating warm and cold phases.

The PDO is similar to El Niño (*see* ENSO), but differs in timescale. ENSO events last for 6–18 months; PDO events last for 20–30 years. The two also differ in that ENSO affects mainly the TROPICS, with secondary effects elsewhere, whereas the PDO affects the North Pacific Ocean with secondary effects in the Tropics. Emphasizing the similarity with El Niño and La Niña, warm PDO phases have been nicknamed El Viejo (the old man) and cool phases La Vieja (the old woman).

During warm PDO eras, biological productivity increases in the coastal seas off Alaska, but is suppressed off the North American coast farther south. During cold PDO eras the opposite occurs.

Cold PDO eras predominated from 1890 through 1924 and 1947–76. Warm eras predominated from 1925 through 1946 and from 1977 through about 1995. There were full PDO cold phases from about 1900–1925 and 1950–1975, and full warm phases from about 1925–1950 and 1975 until the mid 1990s. Cold and warm eras lasting just a few years have alternated since the middle 1990s. Some climate scientists suspect that the abrupt shift from a cool phase to a warm phase that occurred in 1976–1977 was responsible for most of the warming that occurred in Alaska since about that time.

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Pacific high An ANTICYCLONE that covers a large part of the subtropical North Pacific Ocean. There is a similar anticyclone over the South Pacific. The Pacific highs are source regions for maritime AIR MASSES. The North Pacific high and North ATLANTIC HIGH together cover one-quarter of the Northern Hemisphere and for six months of each year they cover almost 60 percent of it.

Paleoarchean An era of Earth history that began 3,600 million years ago and ended 3,200 million years ago. The Paleoarchean is the second oldest of the four eras that comprise the ARCHEAN eon. It was a time when the Earth's crust was still forming. (*See* APPENDIX V: GEOLOGIC TIMESCALE.)

Paleocene The epoch of geologic time that began 65.5 million years ago and ended 55.8 million years ago. It is the earliest epoch of the PALEOGENE period. "Paleocene" means "ancient, recent life."

The continents had separated by the start of the Paleocene. Sea levels fell, exposing large areas of land that had previously lain beneath water. Climates were warm, the epoch ending with a rise in TEMPERATURE known as the PALEOCENE–EOCENE THERMAL MAXIMUM. Dense forests covered most of North America and Europe. It was a time of rapid mammal evolution as species radiated to occupy the niches formerly held by dinosaurs, which had become extinct at the end of the CRETACEOUS. (*See* APPENDIX V: GEOLOGIC TIMESCALE.)

Paleocene-Eocene thermal maximum (PETM, Initial Eocene Thermal Maximum, IETM) A CLIMATIC OPTIMUM that occurred approximately 55 million years ago and lasted for less than 100,000 years, at the boundary between the PALEOCENE and EOCENE epochs. At the onset of the climatic optimum, the global mean TEMPERATURE rose rapidly by between 9°F and 14°F (5°C–8°C) and the oceans warmed throughout their depths, not simply at the surface. A second brief temperature rise occurred about 2 million years later.

Scientists are uncertain what triggered the rise in temperature. Some suggested that it followed the release into the atmosphere of 1,500–3,300 billion tons (1,400–2,800 billion tonnes) of METHANE, which triggered the warming through a GREENHOUSE EFFECT. The methane had been held in methane hydrates in sedimentary rocks on the ocean floor. Scientists have proposed various mechanisms by which the methane hydrates might have been induced to release their methane. The most likely cause was astronomical and linked to the cyclical change in the ECCENTRICITY of the Earth's orbit (*see* MILANKOVITCH CYCLES). An alternative explanation is that a surge in volcanic activity released large amounts of CARBON DIOXIDE into the air.

Paleogene The period of geologic time that began 65.5 million years ago and ended 23.03 million years ago. It was the first period of the CENOZOIC ERA.

The climate was warm everywhere throughout the Paleogene. The Indian continental shelf collided with the Asian continental shelf prior to the start of the Paleogene and the Himalayan mountain ranges were already rising, but a land bridge became established for the first time during the EOCENE (*see* PLATE TECTONICS). Shallow seas separated the continents allowing different groups of mammals and birds to evolve on each continent. (*See* APPENDIX V: GEOLOGIC TIMESCALE.)

Paleoproterozoic The first era of the PROTEROZOIC eon of the Earth's history, which began 2,500 million years ago and ended 1,600 million years ago. Complex single-celled organisms appeared during the Paleoproterozoic, including bacteria and cyanobacteria, which formed mats called stromatolites.

These organisms performed PHOTOSYNTHESIS, releasing oxygen as a by-product, and in 2005 Robert E. Kopp and his colleagues at the Division of Geological and Planetary Sciences of the California Institute of Technology suggested that the release of OXYGEN into the atmosphere had dramatic consequences. During the early Paleoproterozoic abundant atmospheric METHANE sustained a GREENHOUSE EFFECT that maintained global TEMPERATURES similar to those of today. The release of oxygen led to the oxidation of the methane, the consequent breakdown of the greenhouse effect, and a rapid drop in temperature. There were three GLACIAL PERIODS between 2,450 million years ago and 2,220 million years ago. The final glacial period, from 2,300 million years ago until 2,200 million years ago was global in extent. Known as the Makganeyene glacial from the South African site where evidence for it was found, it produced a SNOWBALL EARTH. (*See* APPENDIX V: GEOLOGIC TIMESCALE.)

Paleozoic The first era of the PHANEROZOIC eon of the Earth's history, which began 542 million years ago and ended 251 million years ago. By the end of the Paleozoic life had established itself on land, vascular plants had appeared, and most invertebrate groups, including insects, as well as fish, amphibians, and reptiles had evolved.

The supercontinent of Pangaea formed during the Paleozoic. There were two GLACIAL PERIODS. Earth rotated faster than it does now, so the days were shorter, and the TIDES were bigger, because the Moon was closer.

At first the climate was mild, then it became warmer, but the continental shelves, where most organisms lived, grew steadily cooler. By the ORDOVICIAN period most of western Gondwana (what are now Africa and South America) lay at the South Pole. Baltica (Russia and northern Europe) and Laurentia (eastern North America and Greenland) lay in the TROPICS, and Australia and China were in temperate latitudes. The Ordovician ended with a GLACIAL PERIOD. The middle part of the Paleozoic was a time of climatic stability. During the late Paleozoic atmospheric OXYGEN and CARBON DIOXIDE levels fluctuated, and there was one and possibly two glacial periods during the CARBONIFEROUS. The climate deteriorated and the Paleozoic ended with a mass extinction of living organisms at the end of the PERMIAN. (*See* APPENDIX V: GEOLOGIC TIMESCALE.)

parameterization The physical laws governing many processes are well known and can be applied in a general way. If the equations describing such processes are then stored as programming subroutines, they can be called on as required during the construction of a computer MODEL. The use of subroutines in this way is called parameterization.

CLIMATE MODELS impose a grid over the world, typically with grid points 78–155 miles (125–250 km) apart horizontally, and with 10–30 levels 650–1,300 feet (200–400 m) apart vertically. Running the model produces "snapshots" of atmospheric conditions at 30-minute intervals.

Many atmospheric processes take place on a smaller scale than the model grid. These processes include CONVECTION, CLOUD FORMATION, and the transport of heat through the PLANETARY BOUNDARY LAYER. Their development cannot be calculated directly, because the grid is too coarse to accommodate them. Consequently, they can be included in the model only by making the general assumptions stored as subroutines. This is parameterization.

Further Reading

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parcel of air (**air parcel**) A volume of air that can be considered separately from the air surrounding it and from which it is assumed to be physically isolated. The concept is theoretical, since no volume of air can be completely isolated from the air around it, but it is useful in calculating the behavior of the atmosphere. It is used in calculating adiabatic (*see* ADIABAT) changes and in calculations involving the equation of state.

The rate at which the volume of a given mass of air changes is called its mass flux. Air is very elastic, which means that a parcel of air expands, is compressed, and its shape is deformed when it moves against bodies that are denser or less dense than it is. Nevertheless, the total amount of gas (its mass) remains constant. Consequently, when the parcel of air expands, contracts, or is deformed some of its mass flows out of or into the original volume. The rate at which this happens is the mass flux.

An atmospheric cell is a parcel of air inside which the air is moving. In the GENERAL CIRCULATION of the atmosphere, Hadley cells, Ferrel cells, and polar cells are atmospheric cells.

Convective inhibition occurs when the rise of a parcel of air by CONVECTION is checked by an INVERSION. In order to reach its level of free convection (*see* STABILITY OF AIR) the parcel of air must possess sufficient energy to overcome the inhibition.

The TEMPERATURE a parcel of air would have if it were decompressed at the saturated adiabatic LAPSE RATE almost to zero pressure and then recompressed at the dry adiabatic lapse rate to 1000 mb (sea-level pressure) is called its equivalent potential temperature. As the saturated air is decompressed, its temperature falls and its WATER VAPOR condenses. This releases LATENT HEAT of CONDENSATION, warming the air and the warmth is retained, so the equivalent potential temperature is higher than the actual temperature of saturated air at the 1000-mb level. The difference can be estimated from:

$$\theta_e - \theta_w = 2.5q_s$$

where θ_e is the equivalent potential temperature, θ_w is the temperature of saturated air at the 1000-mb level, and q_s is the specific HUMIDITY of the saturated air at the 1000-mb level expressed in grams of water vapor per kilogram of air including the water vapor.

The temperature a parcel of air would have if all the water vapor it contained were condensed from it, the latent heat of condensation were allowed to warm the air, and the pressure remained constant is called its equivalent temperature, also known as its isobaric equivalent temperature. "Equivalent temperature" is also sometimes used as a synonym of equivalent potential temperature.

passive instrument An instrument that measures radiation falling on it (so it is passive), rather than sending out a signal that returns to it.

past weather The weather that has prevailed over the period, usually of six hours, since a weather station last submitted a report. The past weather is reported as a series of numbers between 0 and 9.

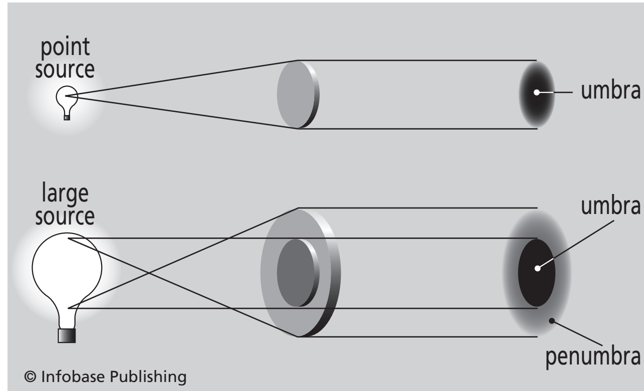
0 Cloud covered half of the sky or less throughout the period
1 Cloud covered more than half the sky for part of the period and less than half for the remainder of the period
2 Cloud covered more than half the sky throughout the period
3 Sandstorm, dust storm, or blowing snow
4 Visibility was less than 0.6 mile (1 km) due to fog, ice fog, or haze
5 Drizzle
6 Rain
7 Snow or a mixture of rain and snow (in Britain, called sleet)
8 Showers
9 Thunderstorms, with or without precipitation

path length The distance that incoming solar radiation must travel between the top of the atmosphere and the land or sea surface. The path length has a value of 1 when the Sun is directly overhead, or 90° above the horizon, and it increases as the angle of the Sun decreases. The path length can therefore be calculated as 1/cosA, where A is equal to 90° minus the angle of the Sun. If the Sun is at 45°, the path length is 1.4, and if the Sun is at 30°, the path length is 2 (90 - 30 = 60; 1/cos60 = 2). Solar radiation travels twice as far through the air when the Sun is 30° above the horizon than it does when the Sun is directly overhead.

pentad A period of five days. Meteorologists and climatologists often use the pentad in preference to the week, because there is an exact number of pentads in a 365-day year (73).

penumbra The less deeply shaded area that lies near the edge of a shadow. The central, totally shaded area is called the umbra. Although they refer to any shadow, the terms are most often applied to ECLIPSES of the Moon or Sun and to SUNSPOTS.

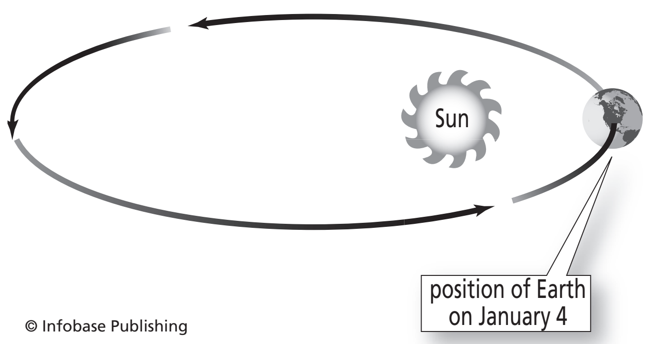
If the source of light is a point, the shadow is sharply defined and there is no penumbra. If the source covers a large area, such as a substantial portion of the sky, then some of the light will illuminate the area around the umbra, producing a penumbra.



The dark center of a shadow is called the umbra. An area adjacent to the umbra that is only partly shaded is called the penumbra.

perihelion The point in the eccentric solar orbit (*see* ECCENTRICITY) of a planet or other body when it is at its closest to the Sun. At present, Earth is at perihelion on about January 4 each year, but the dates of APHELION and perihelion change over a cycle of about 21,000 years (*see* MILANKOVITCH CYCLES and PRECESSION OF THE EQUINOXES). The Earth receives 7 percent less solar radiation at aphelion than it does at perihelion.

permafrost (pergelisol) Ground that remains frozen throughout the year. In order for permafrost to form, the TEMPERATURE must remain below freezing for at least two consecutive winters and the whole of the intervening summer. Permafrost covers approximate-

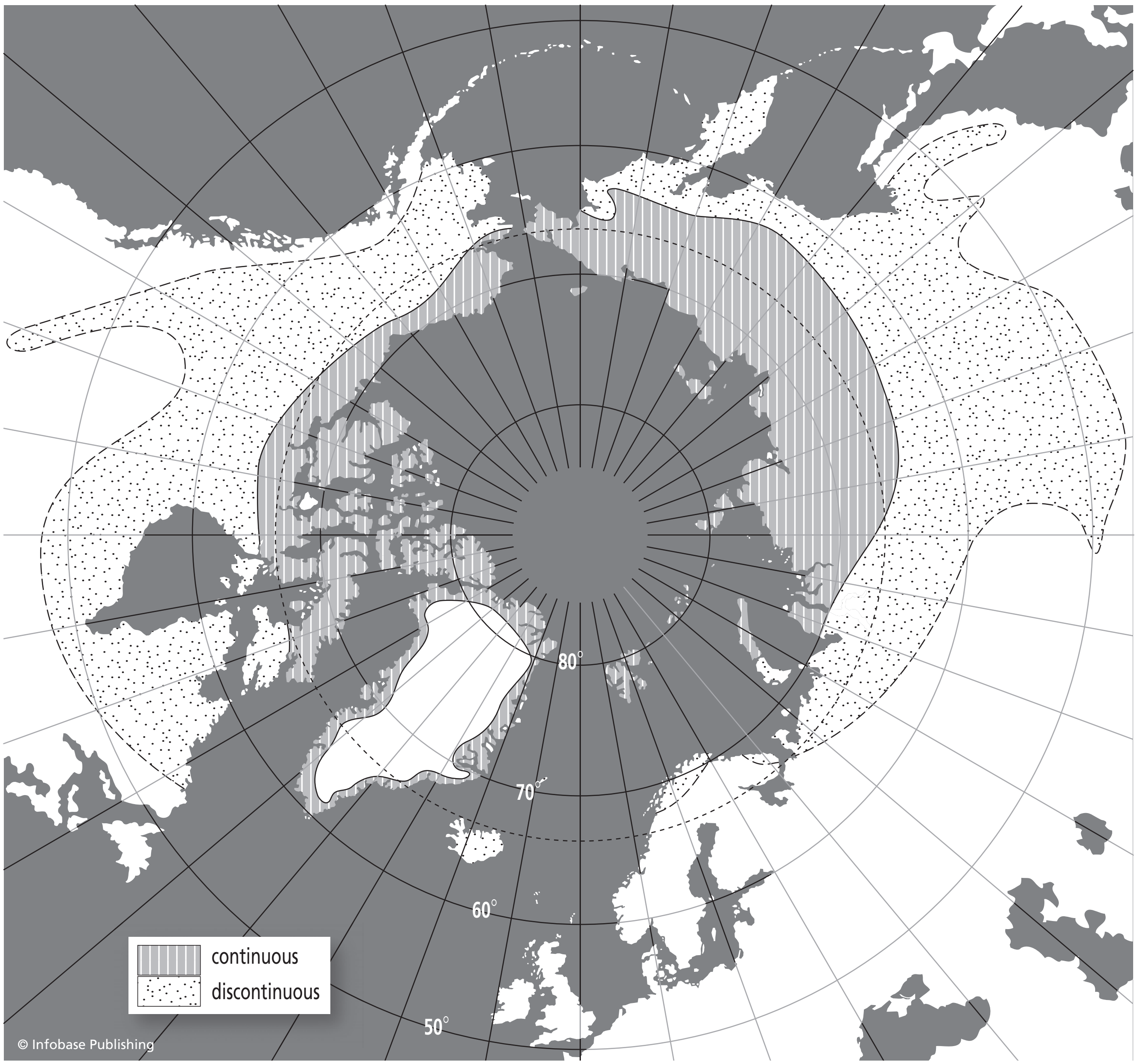


Perihelion is the point in its elliptical orbit at which a body is closest to the Sun.

ly 26 percent of the land area of the Earth, including more than half of the land area of Canada.

The depth of the permafrost layer varies. In Canada it is about 6.5 feet (2 m) thick along the southern edge of the permafrost zone and it is up to 1,000 feet (300 m) thick in the far north. On the North Slope of Alaska the permafrost is 2,000 feet (600 m) thick in places and in parts of Siberia it is up to 4,600 feet (1,400 m) thick.

The soil that lies above a layer of permafrost and that thaws during the summer and freezes again in winter is called the active layer. A layer of frozen ground, or ground containing frozen water, that lies at the base of the active layer in a permafrost region is known as



Together, the regions of continuous and discontinuous permafrost in the Northern Hemisphere cover more than half of Canada and much of Siberia.

the tjaele, or frost table. The tjaele moves downward during the summer thaw in the active layer.

Soil is a poor conductor of heat, and changes in the average air temperature take many years to penetrate. After about 100 years the change will affect material about 500 feet (150 m) below the surface, and it will be 1,000 years before it is felt at 1,640 feet (500 m). Material deep below the surface is so well insulated from temperature changes above the surface that scientists working out past climatic conditions sometimes use it. They take long, vertical cores of soil from the ground and measure the temperature at intervals along them. Some of the Canadian, Alaskan, and Siberian permafrost areas have remained frozen for several thousand years, since the end of the most recent (Wisconsinian or Devensian) GLACIAL PERIOD.

In the northern part of the Arctic, adjacent to the Arctic Circle and to the north of it, the permafrost is continuous. This means that all of the ground is frozen all of the time. Farther south, and covering a much larger land area, the permafrost is discontinuous. It occurs in patches and is found where the average temperature locally is lower than that of the surrounding area, on north-facing slopes that are never exposed to direct sunshine, and on land that is wet for most of the time.

Except for the northernmost tip of the Antarctic Peninsula, all of Antarctica lies within the Antarctic Circle. Ground that is not covered by the ICE SHEET is permanently frozen. Apart from the continent and its offshore islands, there are no other regions of permafrost in the Southern Hemisphere, because there is no large expanse of land in a sufficiently high latitude. Even the southern islands, such as the Falkland Islands (Las Malvinas), have no permafrost.

Permafrost may include areas that remain unfrozen. These are called talik. Where summer temperatures remain above freezing for several weeks or months the upper part of the soil will thaw. This produces a thin active layer in which a few plants can grow. Over the years as plants die and shed leaves, plant material accumulates to form a mat of dead vegetation that insulates the ground below, preventing the summer warmth from penetrating. The existence of an active layer therefore tends to perpetuate the permafrost layer beneath it.

A permafrost layer impedes drainage and, because it is hard as rock, it presents an impenetrable barrier to plant roots.

permeability (**hydraulic conductivity**) The ability of a soil, sediment, or rock to allow water or air to pass through it. Permeability is measured as the volume of water that flows through a unit cross-sectional area in a specified time. Soil permeability is categorized as slow, moderate, or rapid according to the rate of flow and is reported as the distance traveled in one hour. If the water is moving vertically downward through the soil, the process is called percolation. Percolation is reported as the time taken for the water to move a specified distance. The classification system comprises seven classes for both permeability and percolation.

Permeability and the percolation rate depend on the structure of the material through which air or water moves. Sand does not hold water well. Pour water onto a sandy beach on a fine day and the sand is dry again

Permeability and percolation classes

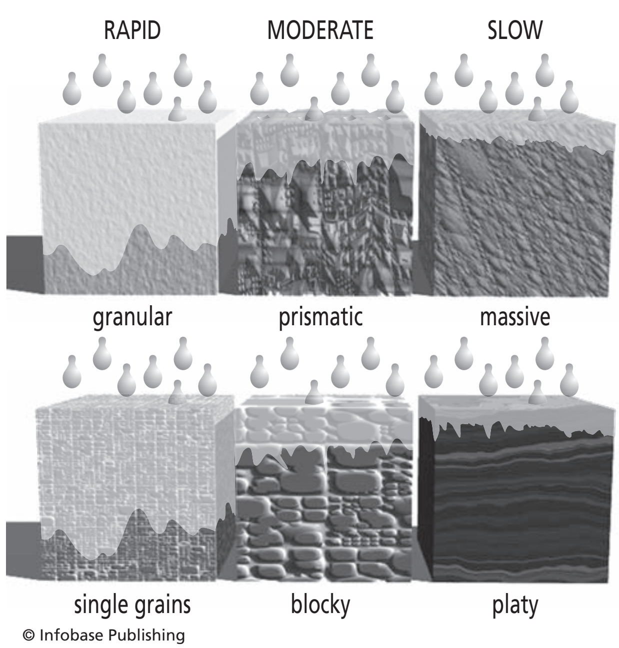
Class	Permeability inches per hour	Permeability cm per hour	Percolation minutes per inch	Percolation minutes per cm
1. very slow	less than 0.05	less than 0.1	more than 1200	more than 470
2. slow	0.05–0.20	0.1–0.5	300–1200	118–470
3. moderately slow	0.20–0.80	0.5–2.0	75–300	30–118
4. moderate	0.80–2.50	2.0–6.4	24–75	9–30
5. moderately rapid	2.50–5.00	6.4–12.7	12–24	5–9
6. rapid	5.00–10.00	12.7–25.4	6–12	2–5
7. very rapid	more than 10.00	more than 25.4	less than 6	less than 2

within at most a few minutes. Clay becomes sodden, because water does not pass through it easily. The difference is due to the size and shape of the particles from which the soil is made.

The spaces between soil particles are called pores, and if all the particles are spherical and the same size, the pore space will amount to about 45 percent of the total volume filled by the particles. This proportion is the same whatever the size of the particles themselves. In a soil, however, the particles are not all of the same size or shape.

If the particles are large, the pore spaces between them will also be large. This will allow water and air to move through the soil rapidly. Gravel and sand do not retain water for very long because they consist of large particles. Sand grains have a granular texture and gravel consists of single stones, or grains. Water permeates and percolates rapidly through them.

If the particles are very small, the amount of pore space is the same, but the individual pores are small. Water tends to be held to the surfaces of the grains by molecular attraction and the distance between one particle surface and the next is so small that there is little room for water to flow past the water adhering to the particles. Some very small particles tend to pack together to form a solid mass. This squeezes out the pore spaces and produces a massive texture. Clay particles pack together, but in layers. The particles themselves are flat, like flakes, but microscopically small. They arrange themselves with their flat sides adjacent. This produces a platy structure that prevents water passing. Water permeates and percolates slowly through soils of these types.



The rate at which water flows through a soil depends on the size and arrangement of the soil particles.

Between the two extremes there are soils made from particles that arrange themselves into prismatic columns. Water is able to move between the columns. Other soils consist of big, irregular particles. These form a blocky structure with channels along which water can move. Water permeates and percolates moderately quickly through soils of these types.

Permeability affects the way soils respond to the weather. Areas where the permeability is rapid will not be susceptible to flooding, because water leaves them quickly. Dry weather can parch the ground just as quickly, however, so there is a relatively high risk of DROUGHT. Where permeability is slow, drought is less of a risk, but flooding is more likely. Also, soils that retain water tend to be cold in early spring, because of the high HEAT CAPACITY of water. This can delay the sowing of spring crops.

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Permian The final period of the PALEOZOIC era of the Earth's history, which began 299 million years ago and ended 251 million years ago. The Permian was named in 1841 by the British geologist Roderick Impey Murchison (1792–1871) after the ancient kingdom of Permia and the city of Perm in the Ural Mountains of Russia, where he found vast deposits of rocks characteristic of the period.

During the Permian all the continents moved together, finally joining to form the supercontinent Pangaea, which was surrounded by the world ocean, Panthalassa. A salty inland sea, called the Zechstein Sea, covered part of Europe, and much of southern and central Europe lay beneath a large bay in the Panthalassa Ocean, called the Tethys Sea.

At the start of the Permian, the Earth was gripped by a GLACIAL PERIOD. ICE SHEETS covered both polar regions and there were glaciers in many parts of Gondwana, the southern continent. Swamp forests extended over much of the TROPICS. By the middle of the Permian, the climate was becoming warmer. The ice sheets and glaciers retreated, and the interiors of the continents became drier. Once the continents had merged, the interior of Pangaea probably had a very dry climate, with marked wet and dry seasons. As the climate became generally drier the swamp forests disappeared.

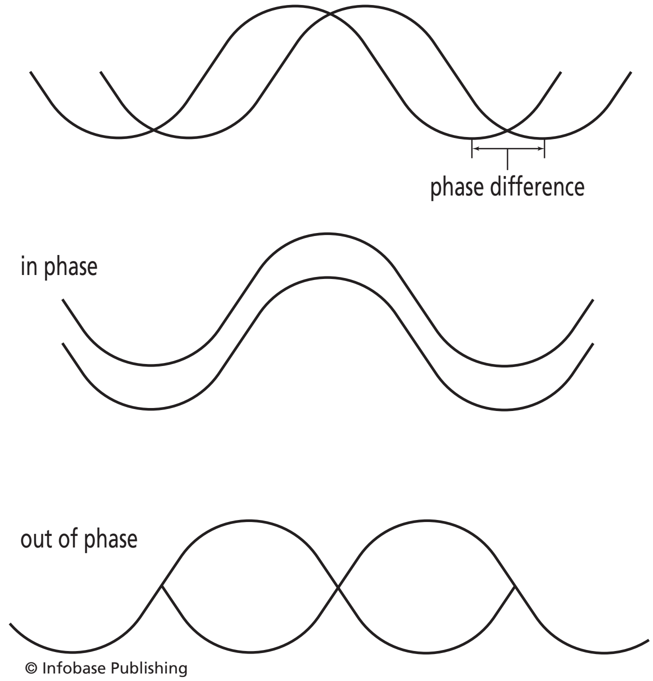
The predominant plants were seed ferns and ferns, together with coniferous trees and ginkgos. The seas teemed with life, including fishes. On land there were ancestors of the reptiles, some resembling crocodiles and turtles, and the ancestors of the mammals. A mass extinction marked the end of the Permian. *See* APPENDIX V: GEOLOGIC TIMESCALE.

Phanerozoic The present eon of the Earth's history, which began 542 million years ago and continues to the present day. The name is derived from the Greek words *phaneros* meaning "visible" and *zoion* meaning "animal." The Phanerozoic is the time of "visible life," although paleontologists now know that living organisms existed long before the start of the CAMBRIAN period, which marks the base of the Phanerozoic. *See* APPENDIX V: GEOLOGIC TIMESCALE.

phase The word *phase* has two meanings. The first describes a part of a system that is of the same composition throughout and that is clearly distinct from all other parts of the same system. A block of ice is a system consisting of one phase (solid), as is a mass of liquid water (liquid) or water vapor (gas). A mixture of water and ice comprises a two-phase system and a mixture of ice, liquid water, and WATER VAPOR comprises a three-phase system. A solution of salt or sugar in water is a single-phase system, because the solution is entirely liquid.

When water changes between gas, liquid, and solid, it is said to change phase. At a pressure of 611.2 Pa (6.112 mb) and a temperature of 32°F (0°C) water can exist as gas, liquid, and solid simultaneously. This is known as its triple point (*see* BOILING) and the triple point of water forms the basis of the definition of the kelvin (0°C = 273.16K; 0K = -273.16°C; *see* TEMPERATURE SCALES and UNITS OF MEASUREMENT).

The stage that a regularly repeating motion has reached is also called a phase. Usually the phase of a periodic motion (*see* WAVE CHARACTERISTICS) is described by comparison with another motion having the same wavelength. If the peaks and troughs of two or more waves coincide, the waves are said to be in phase. If the peaks of one wave coincide with the troughs of the other, the two are said to be out of phase. If the peaks and troughs are between the two extremes of being in phase or out of phase, the distance between them is called the phase difference.



The distance between the troughs and peaks of two waves of the same wavelength is the phase difference between them. The waves are in phase when their peaks and troughs coincide and out of phase when the peaks of one coincide with the troughs of the other.

phenology The scientific study of periodic events in the lives of plants and animals that are related to the climate. Such events include the dates on which deciduous trees come into leaf, crops germinate, flower, ripen, and are harvested, and the dates of arrival and departure of migratory birds.

Phenological events comprise all the familiar signs of the changing seasons. The dates of particular events at places some distance apart can be used to compile a phenological gradient marking the geographic movement of the seasons across a continent or, on a much smaller scale, to measure the effects of such influences as exposure or shade within a garden.

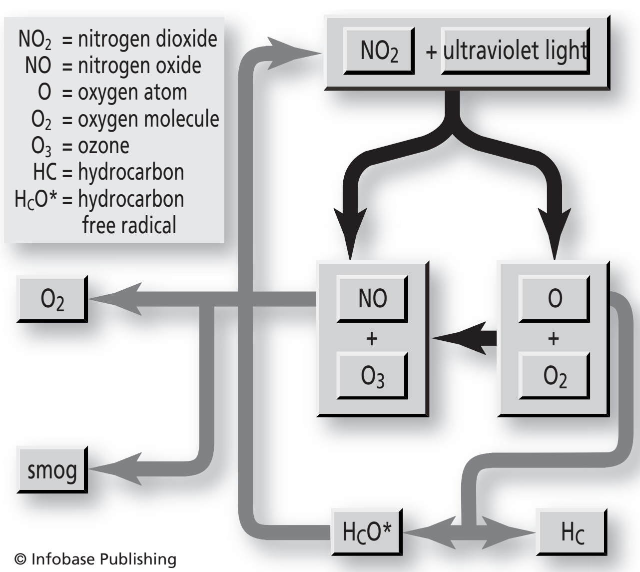
Phenological data collected in Europe over a period of 30 years from the INTERNATIONAL PHENOLOGICAL GARDENS has shown that during this time spring events have advanced to occur six days earlier and autumn events now occur 4.8 days later. The dates of European grape harvests have been of particular value to historians tracing the history of climate and was used extensively by the French historian Emmanuel Le Roy Ladurie.

Further Reading

Ladurie, Emmanuel Le Roy. *Times of Feast, Times of Famine: A History of Climate Since the Year 1000.* New York: Doubleday, 1971.

photochemical smog A form of AIR POLLUTION that occurs in strong sunlight when ULTRAVIOLET RADIATION acts upon hydrocarbon compounds emitted by vehicle exhausts. It is quite different from SMOG of the London type.

The branch of chemistry that studies the chemical effects of electromagnetic radiation, including visible light, is called photochemistry. Many chemical reactions take place only when radiation supplies the energy that is needed to drive them. Photochemical smog is the product of a series of reactions that take place in strong sunlight. OZONE is formed in the stratosphere (*see* ATMOSPHERIC STRUCTURE) by the action of ULTRAVIOLET RADIATION on oxygen (*see* PHOTODISSOCIATION). These are photochemical processes, but the best known and most important photochemical reactions are those in PHOTOSYNTHESIS.



Pollution occurs when some of the atomic oxygen produced by the photolytic cycle combines with unburned hydrocarbons to form hydrocarbon free radicals.

Photochemical smog contains compounds such as aldehydes (compounds containing the -COOH group joined directly to another CARBON atom), ketones (compounds containing the C.CO.C group), and formaldehyde (or methanal, HCHO), which impart a characteristic odor, and nitrogen dioxide (NO_2) and solid particles that cause a brownish haze. Ozone (O_3), aldehydes, and peroxyacetyl nitrates (PAN) cause irritation to the eyes and throats of persons exposed to smog, and plants are damaged by NITROGEN OXIDES (NO_x), O_3, PAN, and ethene (CH_2=CH_2, also called ethylene).

The formation of photochemical smog begins with the photolytic cycle, in which NO_2 is broken down and reformed. Atomic oxygen (O) is produced in the first stage of the photolytic cycle. This is highly reactive and will oxidize hydrocarbons (H_c) to hydrocarbon free radicals (H_cO^*). Free radicals are atoms or molecules that have unpaired electrons as a result of which they are extremely reactive. These react further to reform NO_2, allowing the cycle to continue, and to yield O_2 and the hydrocarbon ingredients of smog. Using oxygen from the photolytic cycle, the reactions are:

$$O + H_c \rightarrow H_cO^* \quad (1)$$

$$H_cO^* + O_2 \rightarrow H_cO_3^* \quad (2)$$

$$H_cO_3^* + NO \rightarrow H_cO_2^* + NO_2 \quad (3)$$

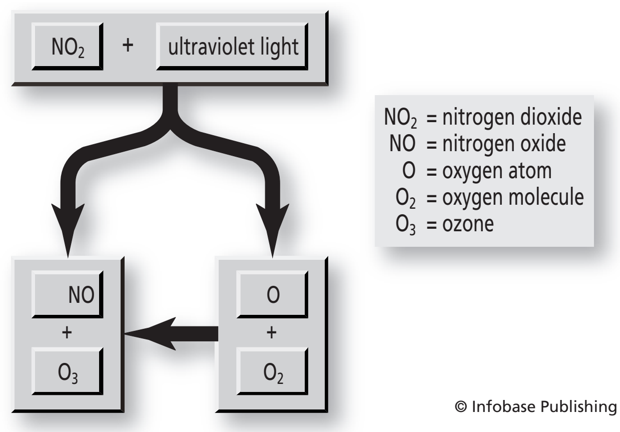
$$H_cO_3^* + H_c \rightarrow \text{aldehydes, ketones, etc.} \quad (4)$$

$$H_cO_3^* + O_2 \rightarrow O_3 + H_cO_2^* \quad (5)$$

$$H_cO_x^* + NO_2 \rightarrow \text{PAN} \quad (6)$$

photodissociation The splitting of a molecule into smaller molecules or single atoms using light as a source of energy. Photodissociation occurs when an atom or molecule absorbs a photon, which is a unit (quantum) of electromagnetic radiation, possessing precisely the energy needed to allow it to break free from the group to which it is attached.

In the upper stratosphere (*see* ATMOSPHERIC STRUCTURE) oxygen molecules (O_2) absorb solar ULTRAVIOLET



Ultraviolet light splits nitrogen dioxide into nitrogen oxide and atomic oxygen. Oxygen atoms then combine with oxygen molecules to form ozone.

RADIATION (UV) at wavelengths (*see* WAVE CHARACTERISTICS) below about 0.3 μm and are photodissociated into single oxygen atoms (O + O). UV radiation at less than 0.23 μm causes the photodissociation of chlorofluorocarbon (CFC) compounds in the stratosphere. In the troposphere, UV radiation at 0.37–0.42 μm photodissociates nitrogen dioxide (NO_2) into nitrogen oxide (NO) and oxygen (O). This photodissociation is followed by the reformation of NO_2 in a process known as the photolytic cycle.

The chemical reactions that comprise the photolytic cycle are:

$$NO_2 + UV \rightarrow NO + O \quad (1)$$

$$O + O_2 \rightarrow O_3 \quad (2)$$

$$O_3 + NO \rightarrow NO_2 + O_2 \quad (3)$$

If hydrocarbons from vehicle exhausts are also present in the air, the natural cycle is disrupted and a range of other compounds are produced, causing PHOTOCHEMICAL SMOG.

photoperiod The number of hours of daylight that occur during a 24-hour period. Except at the equator, this varies with the season. Many plants respond physiologically to changes in the photoperiod. Responding to changes in the photoperiod is called photoperiodism.

The most common responses are those affecting the time of flowering. Some plants will not flower if the daily cycle includes long periods of darkness. These are known as long-day plants (but are really short-night plants), and they flower in late spring and early summer, when the days are lengthening and the nights are growing shorter. Lettuce, wheat, and barley are long-day plants. Strawberries and chrysanthemums are among the plants that flower between late summer and early spring, when days are short and nights are long. They are called short-day plants.

Not all plants are affected by the photoperiod. Tomatoes and cucumbers are among the plants in which the time of flowering is not determined by the duration of daylight. These are called day-neutral plants.

photosynthesis The series of chemical reactions by which green plants (as well as certain bacteria and cyanobacteria) synthesize (construct) sugars, using CARBON DIOXIDE and WATER as the raw materials. The first stage in the process depends on light as a source of energy and is called the light-dependent stage or light stage. The second stage also takes place in light, but it does not use light energy, and so it is called the light-independent stage or dark stage.

The overall set of reactions can be summarized as:

$$6CO_2 + 6H_2O + [\text{light energy}] \rightarrow C_6H_{12}O_6 + 6O_2 \uparrow$$

The OXYGEN is released into the air, indicated by the arrow pointing upward. $C_6H_{12}O_6$ is a simple sugar from which more complex sugars and starches can be made.

The process begins with chlorophyll, the green pigment that is held in bodies called chloroplasts in the cells of plant leaves and some stems. Chlorophyll is a very complex substance with the property of absorbing light energy. When a photon of light possessing exactly the right amount of energy strikes a chlorophyll molecule, one electron in the chlorophyll molecule absorbs that energy and becomes excited. It jumps from its ground state to its excited state and escapes from the molecule, but is immediately captured by a neighboring molecule. An electron is then passed from molecule to molecule along an electron-transport chain until it is used to split water (*see* PHOTODISSOCIATION) into HYDROGEN and oxygen:

$$H_2O \rightarrow H^+ + OH^-$$

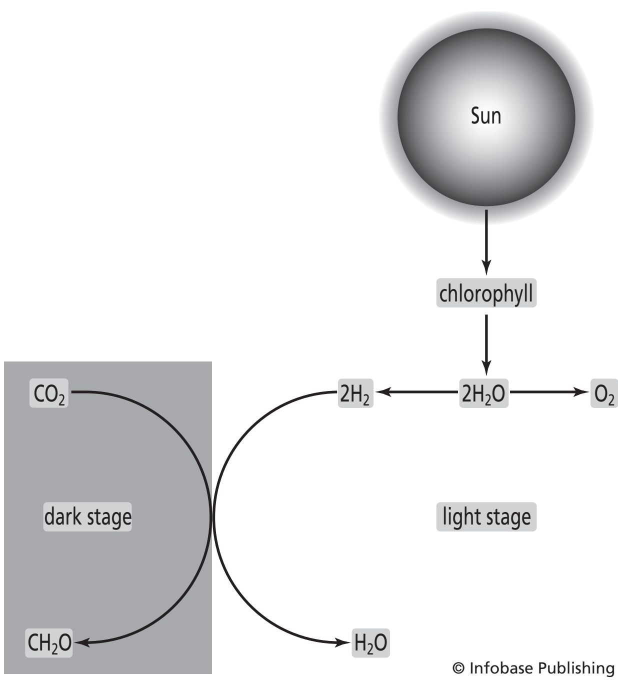
Having lost an electron, the chlorophyll molecule carries a positive charge. The hydroxyl ion (OH) produced by the photodissociation of water carries a negative charge in the form of an extra electron. The hydroxyl ion passes this electron to the chlorophyll. Both hydroxyl and chlorophyll are then neutral and hydroxyls combine to form water:

$$4OH \rightarrow 2H_2O + O_2 \uparrow$$

The oxygen is released into the air. Free hydrogen atoms attach themselves to molecules of nicotinamide adenine dinucleotide (NADP), converting it to NADPH. This completes the light-dependent stage.

NADP loses its hydrogen again during the light-independent stage, and the NADP then returns to the light-dependent stage, ready to be used again.

The light-independent stage begins when a molecule of carbon dioxide (CO_2) becomes attached to a molecule of ribulose biphosphate (RuBP) in the presence of an enzyme, RuBP carboxylase (usually called rubisco for short). The captured carbon then enters a sequence of reactions that end with the construction of sugar molecules and also of the RuBP with which the process began. Because the RuBP is reconstructed so it can be used again, the sequence of reactions forms a cycle. It is known as the Calvin cycle, because its details were discovered by the American biochemist Melvin Calvin (1911–97). Calvin was awarded the 1961 Nobel Prize in chemistry for this work.



The series of chemical reactions by which plants use the energy of sunlight to manufacture sugars has two stages. Water is broken down into hydrogen and oxygen in the light-dependent stage, and in the light-independent stage carbon from carbon dioxide is used to make sugar.

There are variations on the photosynthetic pathways. If the first product of the light-independent stage, made when CO_2 joins RuBP, is 3-phosphoglycerate, the pathway is called C3, because 3-phosphoglycerate has three carbon atoms. Most plants, including all trees, are C3 plants.

Other plants use the C4 pathway, in which CO_2 combines with phosphoenol pyruvic acid (PEP) rather than RuBP, and the first product is oxaloacetic acid, which has four carbon atoms. This pathway uses more energy than the C3 pathway, but it produces more sugar for a given leaf area, making C4 plants grow faster than C3 plants. C4 plants can also tolerate higher light intensities and lower CO_2 concentrations than C3 plants. Most C4 plants are either grasses or plants that grow in desert. The C4 grasses include sugarcane and corn (maize).

Some desert plants, including cacti and the pineapple, have evolved a third pathway. Plants exchange gases through their STOMATA, but if the stomata are open in bright sunshine, when the rate of EVAPORATION is high, water vapor also passes through them. To minimize the loss of water, these plants keep their stomata closed during the day and open them for gas exchange at night. CO_2 enters at night, combines with PEP to produce oxaloacetic acid, and this is then converted into malic acid ($C_4H_6O_5$, also called hydroxysuccinic acid). The carbon is stored as malic acid until the next day when it is broken down, releasing CO_2, which enters the Calvin cycle.

This method of photosynthesis was first observed in plants belonging to the family Crassulaceae, and it is known as the crassulacean acid metabolism (CAM). The Crassulaceae are succulent herbs and small shrubs that are found mainly in warm, dry regions. The family includes the stonecrops and houseleeks.

Physical Oceanography Distributed Active Archive Center (**PO.DAAC**) The branch of the Data Information System of the EARTH OBSERVING SYSTEM that is responsible for storing and distributing information about the physical state of the ocean. Most of the data held at the PO.DAAC was obtained from satellites. It is technical and intended for research and educational use. The data is available to anyone free of charge, but must not then be sold. The center is part of NASA and is located at the Jet Propulsion Laboratory, California Institute of Technology.

pilot report A description of the current weather conditions that is radioed to air traffic control or to a meteorological center by the pilot or other crew member of an aircraft. The report may consist of nothing more than the height of the CLOUD BASE or cloud top (*see* FLYING CONDITIONS) or the presence of CLEAR AIR TURBULENCE. A full pilot report should contain, in this order: the extent or location of the reported conditions; the time they were observed; a description of the conditions; the altitude of the conditions; and in the case of a report of clear air turbulence or icing, the type of aircraft.

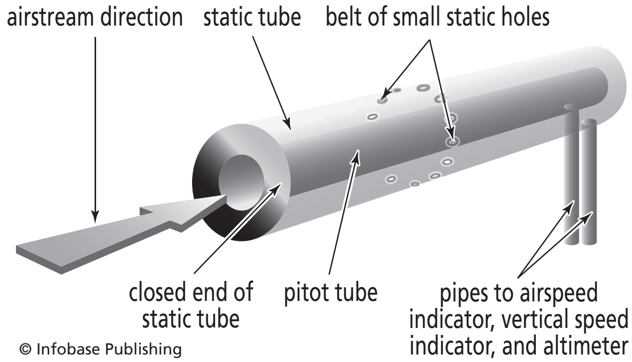
Pine Island Glacier An outlet glacier in the West Antarctic Ice Sheet that is one of the largest outlet glaciers in Antarctica and the glacier with the greatest rate of discharge. The center of the glacier (called the trunk) moves at about 650 feet a year (200 m/yr). The Pine Island Glacier drains 82.5 million tons (75 million tonnes) of ice from the ICE SHEET each year. Between 1992 and 1996 the glacier retreated inland by 3 miles (5 km), and between 1992 and 1999 the interior of the region it drains grew thinner at a rate of 39 inches (100 cm) a year. Near the grounding line, marking the boundary between that part of the glacier which rests on solid rock and that which floats on the sea, the glacier thinned by approximately 5 feet (1.6 m) a year. If the Pine Island Glacier should continue to lose ice at this rate, the glacier could be completely afloat within 600 years and a substantial part of the West Antarctic Ice Sheet might disappear within the next few centuries.

Scientists believe the retreat and thinning of the Pine Island Glacier is caused by internal changes within the glacier itself. It is losing mass at a rate that cannot be explained by present climate change, and the retreat and thinning may be the result of climate changes in the distant past that are only now affecting the glacier and its drainage basin. Tributary glaciers converge about 110 miles (175 km) inland and feed ice into the Pine Island Glacier. The trunk, which is losing about 0.4 percent of its mass a year, sits in a trough about 1,650 feet (500 m) deeper than the bed beneath some of the tributaries. The thinning affects mainly the trunk of the main glacier and not the tributaries.

Pine Island glacier is one of the largest outlet glaciers in Antarctica. It is retreating rapidly, but not because of the present global warming.

pitot tube **(pitot-static tube)** A device that is used to sample air in order to measure the speed with which the air is moving (or the speed with which the pitot tube is moving in relation to the air surrounding it) and the atmospheric pressure. Pitot tubes are used at weather stations, but their most widespread use is on aircraft. Every aircraft carries a pitot tube to supply air to its ALTIMETER, airspeed indicator, and vertical speed indicator (which shows the rate at which the aircraft is climbing or descending). The device was invented by the French physicist Henri Pitot (1695–1771).

A pitot tube comprises two thin-walled tubes, one enclosing the other, and mounted so that the ends of the tubes face into the airstream. Strictly, it is only the tube used to measure the speed of the airflow that should be called a pitot tube. The second tube is a static tube. The end of the pitot tube that faces into the airstream is open. The end of the static tube is closed, but there is a belt of small holes around its circumference. These are located a distance from the forward end of the tube that is equal to not less than five times the diameter of the tube. Usually, the pitot tube is housed inside the static tube.



The outer, static tube encloses the inner, pitot tube. Air from both tubes is fed to the instruments that indicate wind speed or, in an aircraft, airspeed, altitude, and rate of climb or descent (vertical speed).

Air enters the pitot tube through the open end and enters the static tube through the belt of small holes. Pipes conduct the sampled air from both tubes to the instruments.

When air enters the pitot tube, it is brought to rest, exerting a pressure of $\frac{1}{2} \rho v^2$, where ρ is the density of the air and v is its speed. The air pressure in the static tube is exactly equal to the external atmospheric pressure.

The WIND SPEED or airspeed is calculated from the difference in pressure between the two tubes. In an aircraft this is shown on the airspeed indicator. Changes in the pressure in the static tube indicate that the tube is changing its altitude and are used to calculate the vertical speed, which is shown on the vertical speed indicator. Comparing the pressure in the static tube with the sea-level pressure, recorded in the instrument prior to takeoff, gives the height above sea level and is shown as altitude on the altimeter.

Planck's law A description of the relationship between the wavelength of electromagnetic radiation and the TEMPERATURE of the body emitting it that was first stated in 1900 by the German physicist Max Planck (1858–1947). The law states that the intensity of radiation emitted at a given wavelength is determined by the temperature of the emitting body. This can be written as:

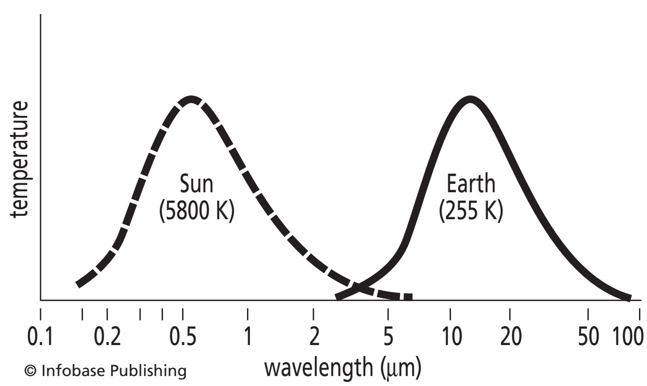
$$E_\lambda = c_1/[\lambda^5(\exp(c_2/\lambda T) - 1)]$$

where E_λ is the amount of energy (expressed in watts per square meter per micrometer of wavelength), λ is the wavelength (in μm), T is the temperature in kelvins, c_1 is the first radiation constant, with the value 3.74 × 10^{16} W/m^2, and c_2 is the second radiation constant, with the value 1.44 × 10^{-2} m/K.

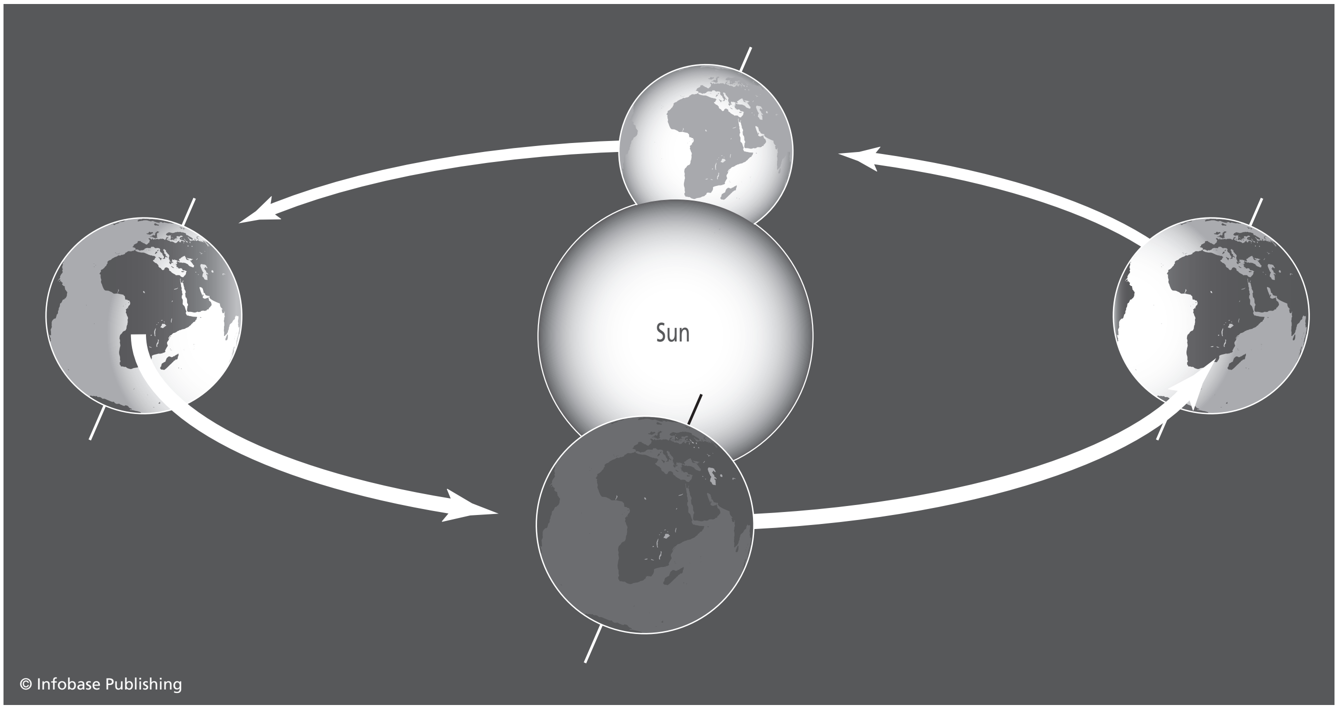
plane of the ecliptic An imaginary disk, the circumference of which is defined by the path the Earth follows in its ORBIT about the Sun. Each day of the year, the noonday Sun is at a slightly different position in the sky from the position it occupied on the preceding day. If its position is plotted for every day of the year on a picture of the landscape that shows a clear view in the direction of the equator, the varying positions of the Sun will appear to follow a path across the sky. This path marks the ecliptic, and the imaginary disk it encloses is the plane of the ecliptic.

If the rotational axis of the Earth were normal (at right angles) to the plane of the ecliptic, the position of the noonday Sun would be the same on every day of the year and, therefore, there would be no SEASONS. In fact, however, the axis is tilted. At present, its angle to the ecliptic is 66.55°, so it is tilted 23.45° from the normal (90 - 66.55 = 23.45), but this angle changes in the course of a cycle with a period of about 41,000 years (*see* MILANKOVITCH CYCLES). Latitudes 23.5° N and S mark the tropics of Cancer and Capricorn and latitudes 66.5° N and S mark the Arctic and Antarctic Circles.

An imaginary circle with a radius drawn from the center of the Earth, through the equator, and projected to the outermost limit of the universe (the celestial



The graph shows the intensity of the radiation emitted at different wavelengths by a body at the temperature of the surface of the Sun compared with that emitted by a body at the temperature of the surface of the Earth. Obviously, the Sun emits far more radiation than does the Earth, but for ease of comparison the graph assumes the same amount for both bodies.



The plane of the ecliptic is an imaginary disk, the edge of which marks the Earth's orbital path around the Sun.

sphere) is called the celestial equator. Because of the Earth's AXIAL TILT, the celestial equator is inclined with respect to the plane of the ecliptic. The latitude of an astronomical body, such as the Sun, measured in relation to the celestial equator, is known as the declination. Declination is the angle north (above, designated +) or south (below, -) of the celestial equator. *See also* MAGNETIC DECLINATION.

planetary boundary layer (**atmospheric boundary layer**) The lowest part of the atmosphere, in which the movement of the air is strongly influenced by the land or sea surface. FRICTION between moving air and the land or sea surface causes EDDIES, making the flow of air turbulent (*see* TURBULENT FLOW). The depth of the planetary boundary layer varies from place to place and from time to time, but it is usually less than about 1,700 feet (519 m).

The lowest approximately 10 percent of the total depth of the planetary boundary layer—about 170 feet (52 m)—is called the friction layer, or surface boundary layer. Turbulent flow within the friction layer ensures thorough mixing of the air. Consequently, the characteristics of the air in this layer are fairly constant throughout.

The air above the planetary boundary layer, comprising about 95 percent of the total mass of the atmosphere, is called the free atmosphere. Air in the free atmosphere is not directly influenced by friction with the land or sea surface. The planetary boundary layer is sometimes called the shielding layer, referring to the fact that the boundary layer shields the surface from events in the free atmosphere.

The Ekman layer, discovered by the Swedish oceanographer and physicist Vagn Walfrid Ekman (1874–1954; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) is the part of the planetary boundary layer in which the wind blows at an angle across the isobar (*see* ISO-). Within this layer the movement of air is balanced between the PRESSURE GRADIENT FORCE, CORIOLIS EFFECT, and friction. The balance is maintained by the air flowing inward toward a center of low pressure and outward from a center of high pressure. Wind accelerates as it moves toward a center of low pressure due to the conservation of its angular MOMENTUM as it spirals inward. For the same reason, it slows as it spirals outward from a center of high pressure. That is why winds are always stronger around a CYCLONE than they are around an ANTICYCLONE. *See also* UPWELLING.

plasma One of the four states of matter (the other three are gas, liquid, and solid) in which a gas is ionized (*see* ION). The KINETIC ENERGY of particles in a plasma exceeds the energy of attraction (POTENTIAL ENERGY) between particles that are close together. Electrons move rapidly among the particles, neutralizing any net charge, so that each charged particle is surrounded by a cloud of particles with an opposite charge and the electric forces within the plasma are low. These clouds overlap and consequently each particle is linked to many others. Particles rarely collide.

Plasmas occur naturally in the atmospheres of stars, including the Sun, and constant bombardment by the charged particles of the SOLAR WIND continuously creates a plasma in the region of space immediately surrounding Earth. The MAGNETOSPHERE consists entirely of plasma.

plate tectonics The theory that describes the surface of the Earth as a number of solid sections that are able to move in relation to one another, thereby causing the deformation of rocks and the production of new structures. The sections are called "plates," and "tectonics" (from the Greek *tektonikos,* meaning "carpenter") is a geologic term referring to rock structures resulting from deformation and the forces that produce them.

The theory of plate tectonics explains the presence of features that must have formed under conditions very different from those of today. Limestone rocks, for example, are abundant in many parts of the world. Limestone forms only by the heating and compression of sediments on the floor of a shallow sea. Consequently, limestone regions must once have been covered by sea. Coal measures can form only in mud beneath shallow coastal waters in the TROPICS. Areas where coal is found, such as the northern United States, northern Europe, Russia, and China, must once have lain close to the equator. Other places, such as parts of Devon in southwestern England, have rocks of a type that forms only in hot, dry deserts.

The theory developed slowly over a long period. Geographers had speculated about how it could be that the shape of the continent of Africa looks as though it would fit snugly against Central and South America, but assumed this was mere coincidence. Then, in 1879, Sir George Darwin (1845–1912, a son of Charles Darwin) suggested that the Moon might have formed by breaking away from the Earth. Geologists then believed that the mantle, beneath the solid rocks of the Earth's crust, is liquid, and in 1882 and 1889 the Rev. Osmond Fisher (1817–1914) proposed that the Pacific Ocean might fill a basin caused by the removal of the rocks that formed the Moon. Osmond thought the continents to either side of the Pacific might have moved together to close the gap, and that this movement might have caused a split that widened to form the Atlantic. The most comprehensive proposal for the motion of continents was made some years later, however, by Alfred Wegener (1880–1930; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). But by then opinions had changed. Geologists believed the mantle to be solid and Wegener's idea was dismissed.

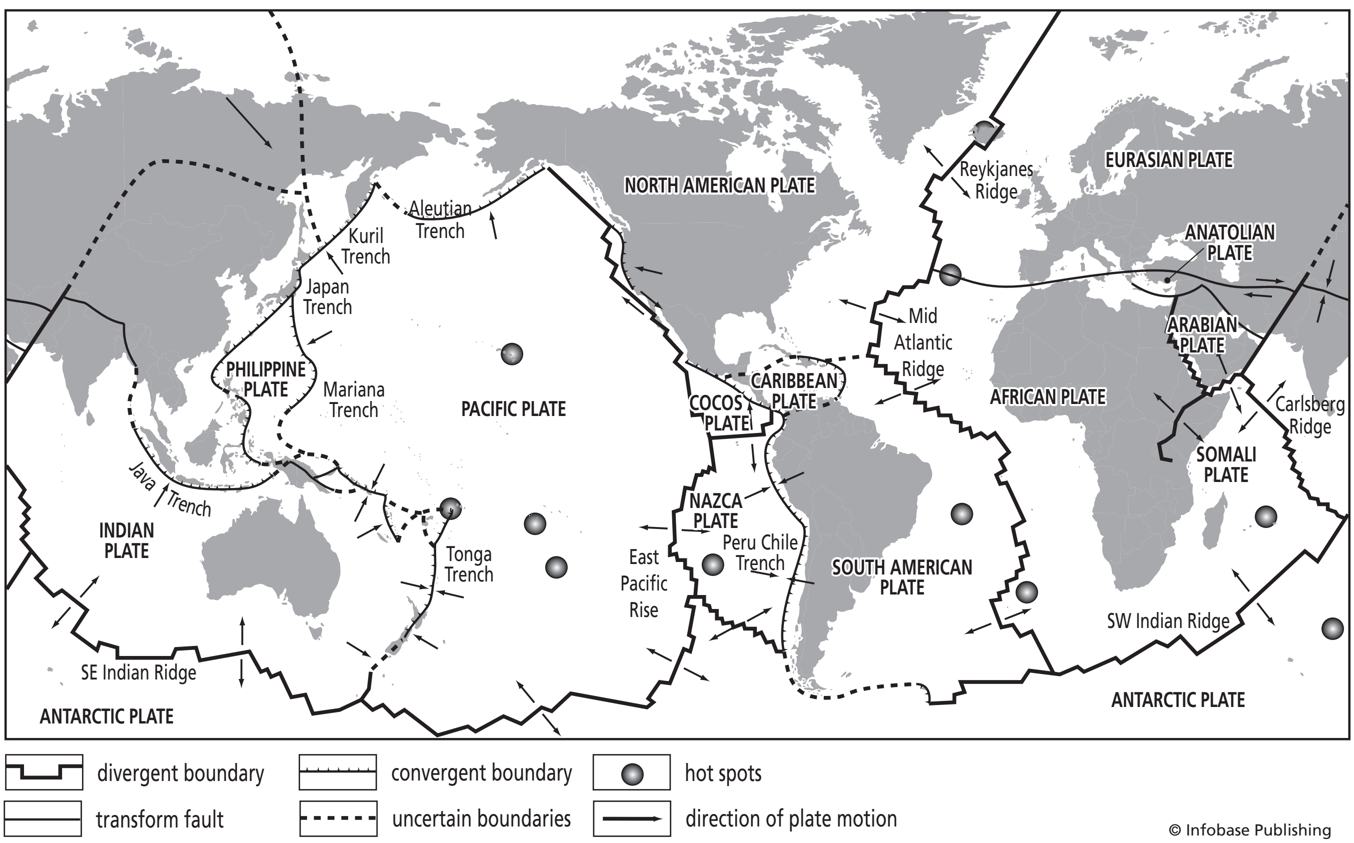
Support for Wegener's idea began to grow in the middle 1940s, when scientists first acquired the technological means to study the floor of the deep oceans. The most important development was the discovery that rocks to either side of the ridges running across all the major ocean basins formed distinct bands of reversed magnetic polarity. Scientists knew that from time to time the Earth's magnetic field reverses its polarity, so that north becomes south and south north. Mineral grains in molten rock align themselves with the magnetic field, and as the rock solidifies, their magnetic orientation becomes fixed. The magnetic bands in the rocks of the ocean floor matched each other on either side of the ridges. This suggested that over a long period new, molten rock had emerged from the ridges and solidified on either side, and that the ocean floor had move away from the ridges to accommodate the new rock. In 1963, an American naval oceanographer, Robert Sinclair Dietz (1914–95) called this "seafloor spreading." It was in 1967 that Professor Dan McKenzie (born 1942) of the University of Cambridge brought all the different strands of evidence together and proposed the theory of plate tectonics.

The theory proposes that the Earth's crust is formed from a number of major and minor plates. Some of the plates are relatively thin and made from dense rock. These form the floors of the oceans. Other plates are much thicker and made from rocks that are less dense. These form the continents, rising above the sea.

Geologists differ in the way they classify some of the plates, but most now consider that there are eight major plates: the African, Eurasian, Pacific, Indian, North American, South American, Antarctic, and Nazca plates.

The Cocos, Caribbean, Somali, Arabian, Philippine, and Scotia plates are smaller and are classed as lesser plates. In addition, there are minor plates such as the Juan de Fuca and Gorda plates, as well as microplates and fragments of former plates. The plates are made from solid rock, and they move because of convection currents in the hot rock of the mantle. In some places where the oceanic crust is thin there are hot spots, where VOLCANOES are especially active. Earthquakes and volcanism are also common in the vicinity of plate margins.

Plate margins are of several types. At divergent, or constructive, margins plates are moving apart and new crustal rock is being added. At convergent, or destructive, margins plates are moving toward each other. The denser oceanic rock sinks beneath the lighter continental rock, and dense rock that has already descended below the crust drags the rest of the plate behind it. This process is called subduction. As the oceanic plate sinks, the sedimentary rock and loose sediment on the surface of the subsiding rock is scraped off, forming mountains along the coast of the continent. When two continental plates collide, both are of equal density and neither can sink below the other, so the rocks of both are crumpled upward to form mountains. The Himalayas are the most recent mountains to be produced in this way, by the collision between the Indian and Eurasian plates that began about 40 million years ago. The Indian plate is still moving northward, so the mountains are still rising, although they are eroding almost as quickly owing to the extreme weather conditions to which they are exposed. At other margins, the plates are moving parallel to each other but in opposite directions, a process that produces a type of rock fracture called transform faulting.



The major plates into which the Earth's crust is divided, with ridges at which plates are separating and new rock is being added, and trenches at which one plate is being subducted beneath its neighbor. At transform faults the plates are moving past one another in opposite directions.

Plate movements cause the continents to change their positions. About 200 million years ago, for example, there was just one "supercontinent" called Pangaea (from the Greek *pan,* meaning "all," and *gi,* meaning "Earth") and one ocean called Panthalassa (*thalassa* means "sea"). An arm of the sea, called Tethys, penetrated deeply into Pangaea, partly separating it into a northern part, called Laurasia, that contained all the present northern continents, and a southern part, called Gondwana, containing the southern continents. About 180 million years ago, Pangaea began to break apart. North America broke away first from Africa and about 150 million years ago from Europe.

Pleistocene The epoch of geologic time during which the most recent sequence of GLACIAL PERIODS occurred. The Pleistocene epoch began about 1.81 million years ago and ended about 11,000 years ago, which is when the Wisconsinian glacial ended. The Pleistocene epoch was followed by the HOLOCENE EPOCH, which continues to the present day. Together these two epochs comprise the PLEISTOGENE period. Technically, the start of the Pleistocene is defined by a change in the Earth's magnetic polarity and the extinction of certain microscopic marine organisms and first appearance of others. The end is defined as exactly 10,000 radiocarbon years ago (*see* RADIOCARBON DATING), which is equivalent to about 11,000 calendar years ago.

When the Pleistocene was first identified, its climate was thought to have been uniformly cold throughout. It was equated with the "Great Ice Age," the existence of which was discovered by Louis Agassiz (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). In fact, the climate was much more complex. About 3 million years ago, the continents of North and South America joined, closing a seaway that had previously separated them. This created conditions that allowed glaciations to develop in the Northern Hemisphere. The first of these occurred about 2.36 million years ago (during the Pliocene epoch of the NEOGENE period). During the Pleistocene, glaciations occurred at intervals of about 100,000 years, and their onset and ending was driven by the astronomical events of the MILANKOVITCH CYCLES. During each glaciation, ICE SHEETS extended approximately to a line running from Seattle to New York and from London to Berlin and Moscow. Sea levels fell to about 395 feet (120 m) lower than they are today, because of the large amount of water held as ice.

Between glaciations there were INTERGLACIALS. These were episodes of warmer climates lasting an average of 10,000 years. During some interglacials, including the Sangamonian interglacial, which was the one prior to the present, Flandrian interglacial, TEMPERATURES were markedly higher than those of today. About 528,000 cubic miles (2.2 million km^3) of ice melted from the West Antarctic Ice Sheet during the Sangamonian, raising the sea level to about 20 feet (6 m) above its present level, but the East Antarctic and Greenland ice sheets remained intact. *See* APPENDIX V: GEOLOGIC TIMESCALE.

Pleistogene The period of geologic time that began about 1.81 million years ago and that continues to the present day. Because this is the period during which human beings evolved, some people have suggested the period be called the Anthropogene. The Pleistogene is the third period of the CENOZOIC era and comprises the PLEISTOCENE and HOLOCENE epochs. *See* APPENDIX V: GEOLOGIC TIMESCALE.

Climatostratigraphy is the study of traces of soil and living organisms found in sedimentary rocks that were formed during the Pleistogene. These rocks can be dated (*see* RADIOMETRIC DATING) and the fossils and other materials found in them provide clues to the climatic conditions at the time the sediments were deposited.

Pliocene The epoch of geologic time that began about 5.3 million years ago and ended about 1.81 million years ago. It comprises the most recent epoch of the NEOGENE period.

During the Pliocene, North America and South America became joined by a land bridge. Otherwise a map of the Pliocene world is very similar to a map of the modern world. Climates everywhere began to grow cooler during the preceding MIOCENE epoch, and this trend continued throughout the Pliocene. The Antarctic ice cap began to form, but Antarctica was not yet completely frozen. Marine invertebrates typical of arctic waters appeared as far south as Britain. With falling temperatures, grasslands spread and forests retreated. Consequently, grazing mammals such as cattle, sheep, antelopes, and gazelles became more numerous and more widespread. Saber-toothed cats hunted them. *See* APPENDIX V: GEOLOGIC TIMESCALE.

pluvial A prolonged period of increased PRECIPITATION that affects a large region. The increase in precipitation is caused by increased EVAPORATION from the ocean and is associated with generally warmer conditions. Pluvial periods are separated by drier interpluvial periods.

Increased rainfall during a pluvial may produce lakes that subsequently disappear when drier conditions return. These are known as pluvial lakes. Lakes that formed during the PLEISTOCENE and of which only traces now remain are the best known examples of pluvial lakes. The lakes formed during warmer INTERGLACIAL episodes, when rainfall increased, glaciers retreated, ICE SHEETS melted, and rivers flowed, carrying vast quantities of water that accumulated in depressions hollowed out by the ice. In North America, lakes in the Great Basin expanded to form large inland seas, such as LAKE BONNEVILLE and Lake Lahontan, and extensive lakes also formed in East Africa. All of these lakes reduced greatly in size during the interpluvial periods that separated the pluvials.

Poisson's equation An equation from which it is possible to calculate the TEMPERATURE of a PARCEL OF AIR at any height, provided the air is on a dry ADIABAT. The equation is:

$$(T \div \Phi) \times c_p \div R = p \div p_o$$

where T is the actual temperature, Φ is the POTENTIAL TEMPERATURE, R is the specific gas constant of air, c_p is the specific heat at constant pressure, p is the pressure at the position of the air parcel, and p_o is the surface pressure. The equation was devised by the French mathematician Siméon-Denis Poisson (1781–1840).

polar high The persistent region of high surface atmospheric pressure that covers the Arctic Basin and Antarctica. In winter it consists of continental arctic (cA) air (*see* AIR MASS) over both polar regions. In summer the cA air continues to cover Antarctica, but maritime arctic (mA) air covers the arctic. The polar highs are the source of the polar easterlies (*see* GENERAL CIRCULATION).

polar low (**polar hurricane**) A small, intense CYCLONE that forms during winter in the cold AIR MASS on the side of the polar FRONT that is nearest the pole. Polar lows usually bring heavy hail and snow, and winds of up to gale force.

Polar lows are 125–500 miles (200–800 km) in diameter and develop when large amounts of very cold air spill out from the ice-covered continents across a markedly warmer sea. A small, upper-level TROUGH may also need to be present to trigger the disturbance that grows into the cyclone.

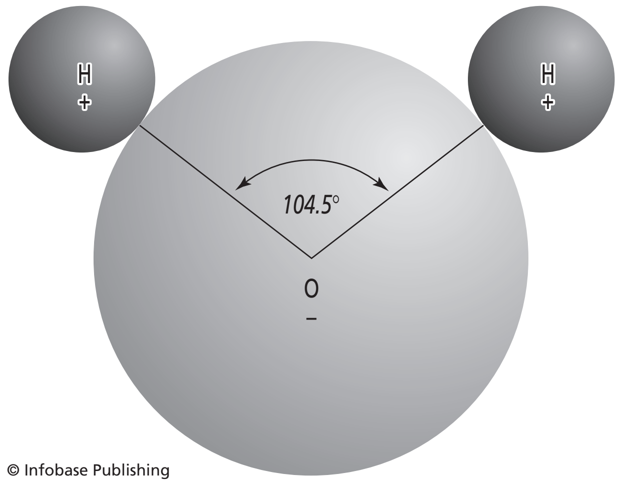
Once it has formed, a polar low is similar to a TROPICAL CYCLONE in many respects, although it is much smaller. Like a tropical cyclone, it is circular, generates strong winds, and has a cloud-free center surrounded by towering cumuliform cloud (*see* CLOUD TYPES) sustained by CONVECTION and extending to the tropopause (*see* ATMOSPHERIC STRUCTURE). Air flows outward from the cyclone at high level, producing cirrus cloud. A polar low dissipates quickly when it crosses land.

In other respects a polar low is unlike a tropical cyclone. From its first appearance, it reaches its full strength within 24 hours or less. It travels at up to 30 knots (34.5 MPH, 55.5 km/h), which is much faster than a tropical cyclone, and it lasts for no longer than 48 hours before it reaches land and dies.

Polar lows occur in many parts of the North Pacific and North Atlantic Oceans and also over the Tasman Sea, close to New Zealand. So far as is known, they rarely form over the Southern Ocean. They are most common in the Greenland, Norwegian, and Barents Seas, but sometimes they also form on the western side of Greenland and in the Beaufort Sea, to the north of Alaska.

polar molecule A molecule in which the electromagnetic charge is separated, so that one end of the molecule carries a positive charge and the other end carries a negative charge, although the molecule as a whole is neutral. Because it carries charge at its ends, the molecule is a dipole.

The WATER molecule is polar. This is because its two HYDROGEN atoms share their single electrons with the OXYGEN atom. Lines drawn from the two hydrogen atoms to the center of the oxygen atom meet at an angle of 104.5°, so both hydrogen atoms are positioned on the same side of the oxygen atom. This gives the oxygen side of the molecule a negative charge and the hydrogen side a positive charge, and it is this char-



Water molecules (H_2O) are polar because their hydrogen atoms share electrons with the oxygen atom, and both hydrogens, bearing positive charge, are on the same side of the oxygen, which carries negative charge.

acteristic that allows water molecules to form hydrogen bonds (*see* CHEMICAL BONDS) and liquid water to act as a very efficient solvent.

Polar Pathfinder Program A program that uses sensors on orbiting satellites to monitor the polar regions. The program was initiated by the EARTH OBSERVING SYSTEM program.

Climatic changes on a global scale are likely to be amplified in the Arctic and Antarctic, because ICE SHEETS and the area of SEA ICE are especially sensitive to changes in temperature. There is a second reason why changes due to the GREENHOUSE EFFECT are expected to appear first and most strongly at the poles. Because it is so cold, polar air is extremely dry. WATER VAPOR is the most important greenhouse gas, but its atmospheric concentration varies widely from place to place and from hour to hour, so it tends to mask signals from other greenhouse gases. Those signals, for example from a rising concentration of CARBON DIOXIDE, will therefore be detectable in very dry air some time before they are evident in the moister air of lower latitudes. These considerations make it highly desirable to maintain a close watch on the polar regions.

The advanced very high resolution radiometer (AVHRR, *see* SATELLITE INSTRUMENTS) and the TIROS operational vertical sounder (TOVS) carried on the TELEVISION INFRARED OPERATIONAL SATELLITE have been acquiring data for many years. There is a continuous record since 1982 from the AVHRR and from 1978 from the TOVS. In addition, there are data from microwave sensors from 1978.

Little use has been made of these data, because they are so voluminous that individual laboratories found them too costly to acquire and process, and the data contained errors. The Polar Pathfinder Program aims to remedy that situation by supplying raw data that are consistently calibrated to allow data from different instruments to be compared.

Further Reading

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polar stratospheric clouds (PSCs) Clouds that form in winter over Antarctica and, less commonly, over the Arctic. They occur in the stratosphere (*see* ATMOSPHERIC STRUCTURE) at a height of 9–15.5 miles (15–25 km). Usually they are too thin to be visible, but when the Sun is about 5° below the horizon they can sometimes be seen as nacreous clouds (*see* CLOUD TYPES). What is known about them has been discovered by means of LIGHT DETECTION AND RANGING (LIDAR).

There are two principal types of PSC, known as Type 1 and Type 2, and there are two or possibly three varieties of Type 1 PSCs, known as Types 1a, 1b, and 1c. All Type 1 PSCs form at about 9 miles (15 km) altitude in air that is just above the frost point. At this height the frost point temperature is about -109°F (195K, -78°C). As the temperature falls below the frost point, Type 1 clouds begin to form rapidly, with very small ICE CRYSTALS acting as FREEZING NUCLEI. The source of the WATER VAPOR to produce the ice crystals is not known, but it may result from the oxidation of methane (CH_4) to carbon dioxide (CO_2) and water (H_2O). The Type 1 particles then grow rapidly as nitric acid (HNO_3) and more water vapor condense onto them. The resulting solution may be either liquid or solid, depending on the conditions around it.

Type 1a clouds are believed to consist of irregularly shaped, liquid particles about 0.004 inch (0.1 mm) in diameter made from approximately one molecule of HNO_3 to three molecules of H_2O.

Type 1b clouds are made from much smaller (about 0.00004 inch, 0.001 mm) liquid particles that are spherical and probably made from a mixture of sulfuric acid (H_2SO_4) and HNO_3 dissolved in water. There may also be Type 1c clouds, made from solid crystals of HNO_3 and water.

Type 2 PSCs are made from ice crystals. These PSCs form at lower temperatures and, therefore, at a greater altitude, most commonly at around 15.5 miles (25 km), where the temperature is about -121°F (188K, -85°C). Type 2 PSCs occur over Antarctica, but are very rarely observed over the Arctic, where winter temperatures seldom fall low enough for them to form.

The chemical reactions involved in the removal of OZONE from the OZONE LAYER take place on the surface of PSC ice crystals. Chlorine (Cl) is present in the stratosphere in two forms that are fairly inert chemically. These are hydrochloric acid (HCl) and chlorine nitrate ($ClONO_2$). On the surface of PSC particles they are converted into the much more reactive forms Cl_2 and HOCl by the reactions:

$$HCl + ClONO_2 \rightarrow HNO_3 + Cl_2$$

$$ClONO_2 + H_2O \rightarrow HNO_3 + HOCl$$

In both reactions, the HNO_3 remains inside the cloud particles. HOCl then reacts further to release free atomic chlorine (Cl).

Chlorine then reacts to remove ozone (O_3) in a series of steps.

$$Cl + O_3 \rightarrow ClO + O_2$$

This reaction takes place twice, to yield two molecules of ClO, which combine and in two subsequent reactions release 2 chlorine atoms.

$$ClO + ClO + M \rightarrow Cl_2O_2 + M$$

$$Cl_2O_2 + hv \rightarrow Cl + ClO_2$$

$$ClO_2 + M \rightarrow Cl + O_2 + M$$

where *M* is any air molecule and *hv* is a quantum of solar energy of near-UV wavelength.

NITROGEN OXIDES (NO_x) are also removed by reactions on the surface of PSC particles. The process is called denoxification, and it is important because nitrogen dioxide (NO_2) removes chlorine oxide (ClO), which is a key ingredient in the ozone-depletion process, by the reaction:

$$ClO + NO_2 + M \rightarrow ClONO_2 + M$$

NO_2 changes back and forth into gaseous N_2O_5:

$$4NO_2 + O_2 \leftrightarrow 2N_2O_5$$

Denoxification then removes gaseous nitrogen oxides by the reactions:

$$N_2O_5 + H_2O \rightarrow 2HNO_3$$

$$N_2O_5 + HCl \rightarrow ClNO_2 + HNO_3$$

Nitric acid is also removed, because as the PSC particles grow bigger their weight increases and they start to settle out of the stratosphere.

Further Reading

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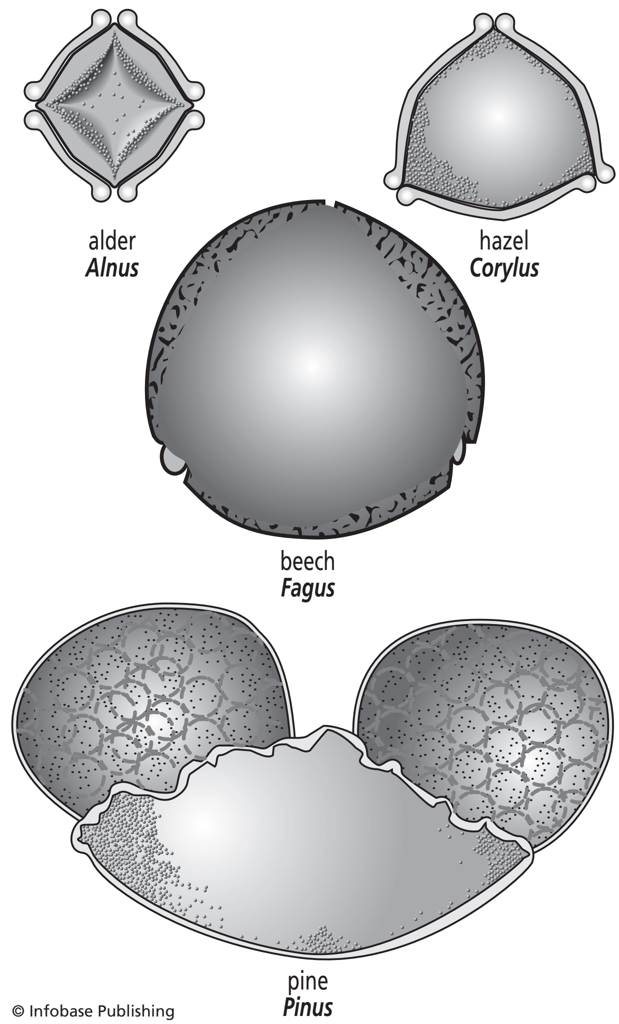
Salawitch, Ross J. "Polar Stratospheric Clouds." Jet Propulsion Laboratory. Available online. URL: http://remus.jpl.nasa.gov/info.htm. Accessed January 20, 2006.

Pole of Inaccessibility The point in the Arctic Ocean that is farthest from land. It lies between the North Pole and Wrangel Island, off the coast of eastern Siberia, and is sometimes taken to be the center of the Arctic.

pollen Pollen grains are the male reproductive cells of seed plants. Seed plants are plants that reproduce by producing seeds, rather than SPORES. The group includes the coniferous plants (gymnosperms) and the flowering plants (angiosperms). Pollen consists of individual pollen grains, which plants produce in vast numbers. Many insect-pollinated plants produce pollen grains that are sticky or barbed, to make them adhere to the pollinator. Pollen from wind-pollinated plants is usually smooth.

Most pollen lives for only a very short time (a few hours in the case of grasses), but the protective outer coating, called the exine, resists decay. Under ideal conditions, the exteriors of pollen grains can be preserved for many thousands of years.

A pollen grain is contained in a coat with two layers. The inside layer, called the intine, is soft, but the outer layer, the exine, is very tough and often sculptured. Grooves, called colpi (singular colpus), form patterns on the exine that are characteristic for particular plant families and in some cases for genera and even species. The pollen grains of some plants have pores in the exine through which the intine protrudes, and this adds to the markings on the exine. These sculptured shapes and markings are visible under a powerful microscope (usually at a magnification of at least ×300 and more often ×400 or ×1000). The markings on pollen grains allow palynologists to identify the family of the plant that produced the pollen (for example, the birch family Betulaceae). In some cases it is possible to go further and identify the genus (for example, an alder, *Alnus,* which is a genus of trees belonging to the birch family) or even the species (for example, green alder, *A. crispa*).



Pollen grains from four different tree genera, all drawn to the same scale. Note the air sacs on the pine pollen.

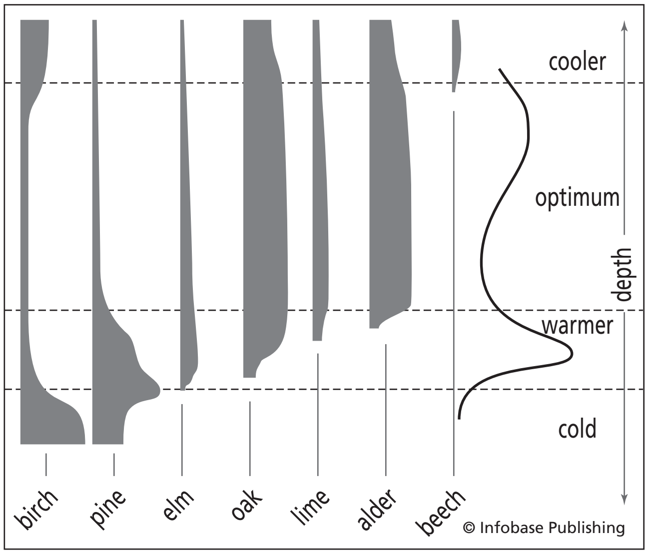
The science of identifying and classifying pollen grains is called palynology, and the interpretation of pollen and spores that are found in sediments is called pollen analysis, although the two terms are often used synonymously.

Pollen analysis is the reconstruction of past climates and environments through the study of pollen grains and plant spores that are recovered from sediments. Pollen analysis began early in the 20th century. The first scientist to apply it was the Swedish geologist Lennart von Post. Palynology is the study of pollen grains, spores, and the shells of some aquatic organisms in order to classify them and discover their distributions. Palynology developed from pollen analysis and is used in many fields, including archaeology, petroleum exploration, and paleoclimatology (*see* CLIMATOLOGY).

Once the pollen has been identified, its presence can be interpreted. The Betulaceae is a family that grows in cool or cold climates, so its pollen indicates that at one time the area had a climate like that of northern Canada or Eurasia, regardless of what the climate is like today. Alders grow near water, and so their pollen indicates that the ground was wet. It might have been a riverbank or the shore of a lake.

An interpretation as simple as this would be unreliable, however. It reads too much into a very small amount of evidence. Pollen can travel, stuck to the skins or coats of animals, or blown by the wind, and so its presence in a particular place does not necessarily mean that that is where the plant actually grew. Conifers are wind-pollinated and produce pollen grains that have two air sacs to increase their BUOYANCY. This pollen can travel very long distances.

Plant species are never alone, however. There is always a community of them, so where pollen is found it usually represents several species. That makes interpretation much more reliable, because of the improbability of pollen from a group of species being brought together by chance. It is much more likely that the plants grew close to each other. They then constituted a life assemblage. After they all died, their pollen became a death assemblage. Its composition is different from that of the life assemblage, because the amount of pollen produced varies greatly from one species to another, the pollen grains themselves are distributed differently, and not all pollen survives equally well. The scientist analyzing the pollen allows for these factors.



A pollen diagram shows how the amount of pollen of particular plant genera changes with depth through a section cut vertically through the soil. This indicates the relative abundance of each genus at different times, from which climatic changes can be inferred.

The pollen is preserved by being buried in soil or lake sediment. It is best preserved under anaerobic, acid conditions, such as those of a peat bog or the bed of a lake. Samples are recovered by drilling vertically through the sediment to extract a core. Organic material found at carefully marked depths can then be dated by RADIOCARBON DATING. This gives a date for the pollen found at those depths. Several samples are needed from each site, and it is usually necessary to count at least 200 pollen grains in each sample.

The absolute pollen frequency (APF) is the actual number of pollen grains that are counted in a unit volume of a sediment and, where the rate of deposition is known, the number per unit time. The pollen grains are those of a particular species, genus, or family of plants. The relative pollen frequency (RPF) is the number of pollen grains belonging to a particular species, genus, or family of plants that can be counted in a given volume of sediment. If the rate of deposition is known in a unit of time, this is expressed as a percentage of either the total amount of pollen present or of the total amount of tree pollen present.

RPF is the most widely used method for comparing pollen diagrams, but APF is more useful than counting the relative pollen frequency where several sites are to be compared and different plants at each site produce the most abundant pollen. The amount and type of pollen present in a sediment that can be dated, for example by radiometric dating, allows the vegetation at that time to be identified. This gives a reliable indication of the type of climate at the time.

A pollen diagram is used to illustrate the pattern of vegetation that occupied a site at particular times in the past. It is compiled from counts of the absolute or relative pollen frequency for certain species, genera, or families of plants. The pollen counts are made from samples of soil that are taken from different depths. Often, the samples are obtained from a cliff face or exposed soil profile in a ditch or other cutting. In the diagram, pollen from each plant is shown as a vertical bar, plotted against depth with the ground surface at the top. The bar varies in thickness according to the amount of that pollen present at each level.

The resulting representation of vegetation types reveals the climatic conditions at different levels, because plants are sensitive to climatic change. If birch (*Betula*) and pine (*Pinus*) predominate, for example, the climate was cold and similar to that of northern Canada and Siberia today. The appearance of elm (*Ulmus*) and oak (*Quercus*) at a higher level, accompanied by a decline in birch and pine, indicates that the climate was growing warmer. Basswoods, also called lime and

Godwin's pollen zones

Years ago	Zone	Plants	Climate
14,000	I	creeping willow	Older Dryas; cold
12,000	II	birch	Allerød; milder
	III	creeping willow	Younger Dryas; cold
10,000	IV	birch, pine	Pre-Boreal; dry
	V	hazel, birch	Boreal; cool, dry
8,800	VIa	hazel, pine	Boreal; cool, dry
8,000	VIb	hazel, pine	Boreal; warmer, dry
	VIc	hazel, pine	Boreal; warmer, dry
7,500	VIIa	alder, oak, elm, lime	Atlantic; warm, moist
5,000	VIIb	alder, oak, lime	Sub-Boreal; cooler, drier
2,800	VIII	alder, birch, oak, beech	Sub-Atlantic; cool, wet

linden, (*Tilia*) grow only in warm temperate climates so their presence indicates a period of warmth. A decline in the abundance of these trees, accompanied by an increase in birch and the appearance of beech (*Fagus*) indicates cooler conditions.

A pollen zone, also called a pollen-assemblage zone, is an assemblage of pollen grains and spores that is considered to be characteristic of a particular climate that was once the climate of a large region. The concept was introduced in 1940 by the English botanist Sir Harry Godwin, and although the zones he proposed are now known to overlap locally and have largely fallen from use, many older textbooks include them.

Godwin proposed eight zones, identifying them with Roman numerals. They extend from the latter part of the Devensian GLACIAL PERIOD until the present day. The eight zones are summarized in the table (bottom, right) on page 364.

pollution Pollution is the act of causing any direct or indirect alteration of the properties of any part of the environment in such a way as to present an immediate or potential risk to the health, safety, or well-being of any living species. The alteration may be chemical, biological, radioactive, or thermal.

Pollution is usually associated with human activities, but it can also occur naturally. For example, volcanic eruptions release large quantities of pollutants, and many plants emit ISOPRENES and terpenes that contribute to the formation of OZONE and PHOTOCHEMICAL SMOG. Certain plants emit METHANE, possibly amounting to 10–30 percent of the total quantity of methane entering the atmosphere, and methane is a greenhouse gas (*see* GREENHOUSE EFFECT).

Chemical pollution occurs when substances are released which are toxic, such as tetraethyl lead, or which are harmless in themselves but engage in reactions that yield toxic products, such as peroxyacetyl nitrate, which one of the chemical compounds formed during the sequence of reactions that result in photochemical smog. Biological pollution involves the release of harmful bacteria, viruses, or fungal spores. These can be carried long distances in the air. Radioactive pollution is caused by the release of radioactive substances that may emit IONIZING RADIATION.

Thermal pollution occurs when gases or liquids are released at a markedly different (almost always higher) temperature than that of the medium into which they discharge. Injecting relatively warmer or cooler gases into the atmosphere can change the way air moves. Discharging hot air can produce a HEAT ISLAND effect that radically alters the local climate. Raising the TEMPERATURE of WATER can harm aquatic organisms, because they depend for RESPIRATION on OXYGEN that is dissolved in water, and the amount of dissolved oxygen water can hold is inversely proportional to the water temperature. *See* AIR POLLUTION.

pollution control The recognition, many years ago, that AIR POLLUTION is a serious problem that must be addressed led to steps to bring it under control. The first requirement was technical. Reducing the emission of pollutants had to be made physically possible, so physical devices were invented that would prevent polluting substances from entering the atmosphere. There is a range of such devices.

Pollutants enter the air from a flue, which is a passage designed to remove the hot waste gases and other by-products of COMBUSTION from an incinerator or other combustion site. It must be built from materials that are capable of withstanding the temperatures to which the combustion products will subject them and arranged in such a way as to produce a steady flow of air to carry the products. Gases passing through the flue are known as flue gases, and most pollution control aims to trap particles or gases before they leave the flue.

A scrubber is a device that removes solid and liquid particles and some gases from a stream of gas. It consists of a space into which water is sprayed or that contains wet packing material. The particles and gas molecules adhere to water molecules or dissolve in the liquid water. Scrubbers are used to take samples of gas streams and to remove potential pollutants from waste gases.

A wet scrubber consists of an ABSORPTION TOWER in which the gas stream is brought into contact with a liquid that absorbs the pollutants. Different liquids are used, depending on the pollutants to be removed.

Caustic scrubbing is a process for the removal of sulfur dioxide (SO_2) from flue gases. It involves passing the gas stream through a solution of caustic soda (sodium hydroxide, NaOH). The SO_2 and NaOH react to form sodium sulfite (Na_2SO_3) and sodium hydrogen sulfite ($NaHSO_3$). The addition of calcium carbonate ($CaCO_3$) then causes the precipitation of insoluble gypsum (calcium sulfate, $CaSO_4$) and leaves the water enriched in sodium carbonate (Na_2CO_3), a harmless substance that is present in most mineral waters. After it has been diluted, the solution can be safely discharged into surface waters.

A bag filter is used to remove small particles from industrial waste gases. It consists of a tube-shaped bag made from woven or felted fabric, up to 33 feet (10 m) long and 3 feet (1 m) wide, and closed at one end. The open end is attached to the pipe carrying the gases. Provided the gas is traveling fairly slowly, the filter can trap more than 99 percent of the particles carried in the waste stream. The material from which the filter is made must be suitable for the temperature of the gas. Natural fibers can be used at temperatures up to 194°F (90°C), nylon up to 392°F (200°C), and glass fibers up to 500°F (260°C).

Bringing two or more substances or objects into contact so that one adheres to the other is called impingement. For example, DUST is made to impinge onto a dust collector. Dry impingement is a technique that is used to remove particulate matter from a stream of waste gases. The gases are blown against a surface to which the particles adhere.

Impingement can be made more efficient if an electrostatic charge (*see* STATIC ELECTRICITY) is applied to the filter, which is then known as an electrostatic filter. Particles bearing a charge are attracted to the opposite charge on the filter.

An electrostatic precipitator is used to remove solid and liquid particles from a gas. The gas is made to flow between two electrodes across which a high voltage is applied. This produces an ELECTRIC FIELD. As the particles pass through the electric field they acquire a charge and move to the electrode bearing the opposite charge, where they are held. Electrostatic precipitators are extremely efficient at collecting small particles and they are used widely to clean industrial emissions.

The second prong in the approach to pollution control aimed to encourage the installation of the available antipollution devices. Companies must purchase these devices and pay for their installation and maintenance. They must also find alternative means for disposing of their unwanted by-products. In a few cases these by-products may have industrial uses and can be sold, but in most cases the cost of disposal must be borne by the company that produces and collects them. A company that accepts all of these costs will find itself at a commercial disadvantage if it competes with other companies that continue to emit pollutants as before. Responsible organizations will recognize the desirability of reducing pollution and will willingly play their part in achieving this, but legislation is needed to compel less responsible organizations to comply, and thereby eliminate their unfair advantage. Regulations are also required to list the forms of pollution that are to be reduced and to stipulate the actions required.

Legislation therefore accompanied the introduction of devices to reduce pollution. Environmental quality standards were introduced to establish the maximum limits or concentrations of polluting substances that are permitted in air, water, or soil. In the United States, there are primary and secondary standards. With an allowance to provide a safety margin, primary standards represent those maxima that present no threat to human health. Secondary standards are those maxima that present no threat to public welfare.

The threshold limit value (TLV) is the greatest concentration of a specified airborne pollutant to which workers may be legally exposed day after day. The TLV is calculated to produce no adverse effect on persons experiencing that level of exposure.

Emissions trading, or trading in permitted pollutant emissions, is an approach to pollution control that has proved highly successful. A political agreement is reached on the total concentration of a particular pollutant that is considered safe and acceptable. Measurements of rates of emission, accumulation, and RESIDENCE TIMES allow scientists to calculate the amount of the pollutant that can be emitted annually if the total environmental burden is not to be exceeded. Scientists also identify the principal sources of the emissions. It is then possible to share the total acceptable emission amounts among the principal sources in the form of emission permits. These stipulate that a particular factory is permitted to emit a specified quantity of the named pollutant in the course of a year. Exceeding emission permits incurs penalties, ranging from a scale of fines to the enforced closure of operations that refuse or are unable to comply.

Every organization with an emission permit may then trade. If a factory's emissions fall below the amount allowed, the company can sell the surplus to another company that wishes to exceed its permitted emissions. Trading quickly establishes a price structure for emission permits, which are then traded much like any other commodity.

The bubble policy introduced in the Clean Air Act (*see* APPENDIX IV: LAWS, REGULATIONS, AND INTERNA-

TIONAL AGREEMENTS) had a similar effect in the United States. This policy allowed companies to agree with the Environmental Protection Agency, which is the regulatory authority, to exceed their allotted emission limit at certain of their installations in return for equivalent reductions in emissions at other installations.

postglacial climatic revertence A period during which the climate became cooler and wetter than it had been previously. The change began abruptly about 2,500 years ago, and the cool, wet conditions have continued to the present day, marking the sub-Atlantic period (*see* HOLOCENE EPOCH).

The onset of the deterioration was marked by a decline in the number of lime trees (*Tilia* species) in England and Wales. Lime trees demand warm conditions. There was also a decline in the number of pine trees (*Pinus* species) in northern Britain, indicating that summers were cool.

Further Reading

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potato blight Two diseases of potatoes that are most likely to cause damage under certain weather conditions. The less serious of the two is early blight, caused by the fungus *Alternaria solani*. It occurs in hot, dry weather. If the temperature remains below about 81°F (27°C), early blight produces brown marks on the leaves of the potato plant, but at higher temperatures it may destroy the foliage.

Late blight is caused by the *Phytophthora infestans* and occurs when the weather is cool and wet, with daytime temperatures between about 50°F and 78°F (10–25°C). *P. infestans* is a water mold, also known as a downy mildew, a funguslike organism classified as an oomycete (Oomycota). Late blight can rapidly destroy the foliage. The tubers then start rotting and soon turn into an inedible brown pulp. It was late blight that caused the failure of the potato crop over Britain in 1845 and 1846 and the potato famine in Ireland.

potential energy The energy that is stored in a body by virtue of its position or state. Energy is stored in a ball that is stationary at the top of an incline and will be converted into KINETIC ENERGY if the ball should start rolling. Gravitational, chemical, nuclear, and electrical energy are all forms of potential energy.

potential temperature The TEMPERATURE a volume of a fluid would have if the pressure under which it is held were adjusted to sea-level pressure, of 1,000 mb (100 kPa), and its temperature were to change adiabatically (*see* ADIABAT). Potential temperature depends only on the actual temperature and pressure of the fluid. It is conventionally represented by the Greek letter Phi (Φ), which is the "phi" in TEPHIGRAM. In METEOROLOGY, the concept of potential temperature is used to calculate the STABILITY OF AIR—the likelihood that air will move vertically with consequent condensation or evaporation of moisture.

The concept also explains why cold air does not sink from the upper atmosphere to the surface. Air temperature decreases with height and according to the GAS LAWS, as the temperature of a mass of gas decreases so does its volume. If a given mass contracts, its DENSITY increases. It would seem, then, that cold air high above the ground is denser than the warmer air close to the ground. If that is so, why is it that the very cold air near the tropopause (*see* ATMOSPHERIC STRUCTURE) remains there?

Suppose that the air is fairly dry, with no clouds in the sky, and that the temperature near to ground level is 80°F (27°C). Up near the tropopause, at a height of 33,000 feet (10 km), suppose that the air temperature is -65°F (-54°C). This is very much colder than the air temperature near the ground. Increase the atmospheric pressure to its sea-level value, however, and as the air is compressed, it will warm at the dry adiabatic LAPSE RATE (DALR) for air, of 5.4°F per 1,000 feet (9.8°C km^{-1}). The consequence of adjusting the pressure is to convert the actual temperature to the potential temperature. At once the reason the cold air does not sink becomes evident.

$$\Phi = (\text{DALR} \times A) + t_t$$

where A is the altitude of the cold air (in this example 33,000 feet) and t_t is its temperature (-65°F). Therefore:

$$\Phi = (5.4 \times 33) - 65$$

$$\Phi = 113.2°\text{F}$$

The potential temperature of the air at the tropopause, of 113.2°F (45°C), is much higher than the actual temperature of air at ground level, which is 80°F (27°C).

The difference between the actual and potential temperature is the reason why the cold air remains aloft.

The wet-bulb temperature that a parcel of saturated air would have if it were taken adiabatically to the 1,000-mb level is called the wet-bulb potential temperature.

The potential temperature of any PARCEL OF AIR is said to be conserved. This means it does not change as a consequence of the vertical movement of the air. Consequently, knowledge of the potential temperature makes it possible to study the thermodynamic characteristics of the air and to represent them in diagrams. The concept is therefore of great importance to meteorologists and is widely used in WEATHER FORECASTING.

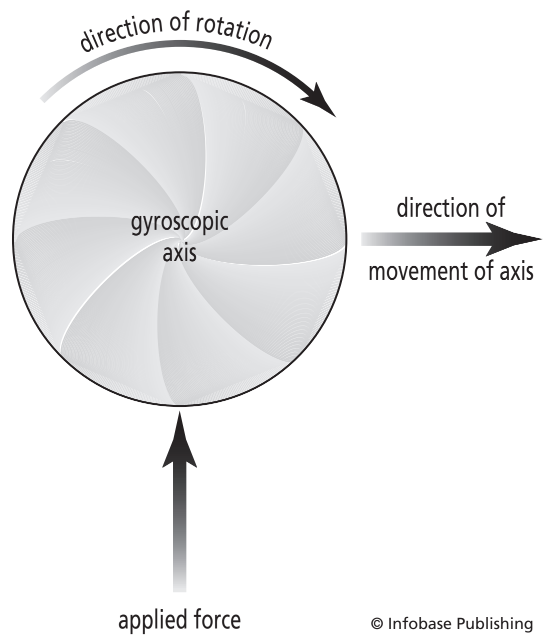
A line joining points of equal potential temperature is called an isentrope, and a surface of equal potential temperature is known as an isentropic surface. Entropy is conserved in all adiabatic processes (*see* THERMODYNAMICS, LAWS OF), so an isentropic surface is one over which entropy is everywhere the same. The mixing of air that takes place across an isentropic surface is called isentropic mixing. Isentropic analysis is a procedure in which winds, pressures, temperatures, and humidities across several isentropic surfaces are extracted from radiosonde data (*see* WEATHER BALLOON).

power-law profile A mathematical expression that describes the variation of the wind with height. Many attempts have been made to devise such a formula, but they tend to fail when the air is very stable. The most successful is probably:

$$u = (u_*/k)[(\ln\{z/Z_o + b/4L'\})(z - z_o)]$$

where u is the wind speed, u_* is the friction velocity, k is the von Kármán constant (*see* WIND PROFILE), ln means the natural logarithm, z is the height, z_o is the roughness length (*see* AERODYNAMIC ROUGHNESS), b is a coefficient, and L' is the length of the gradient, and the gradient is assumed to remain constant with height.

precession of the equinoxes A change in the dates at which the Earth reaches APHELION and PERIHELION and therefore in the position of the Earth in its ORBIT at the EQUINOXES and SOLSTICES. Precession is a property of gyroscopes. When a force is applied to the rotational axis of a gyroscope, the axis moves at right angles to the force in the direction of rotation. Because it is spinning, the Earth behaves as a gyroscope and forces on its



Precession causes the axis of a gyroscope to move at 90° to the direction of a force applied to it.

axis (more strictly on its equatorial bulge) are exerted by the gravitational attraction of the Moon, Sun, and, to a lesser extent, Jupiter. This causes the axis to wobble, like that of a toy gyroscope or spinning top (*see* MILANKOVITCH CYCLES).

If the equator is extended to the edge of the universe, the circle it forms is called the celestial equator. This is at an angle to the PLANE OF THE ECLIPTIC, because of the tilt in the Earth's rotational axis (*see* AXIAL TILT). The equinoxes occur when the Earth reaches the two positions in its orbit at which the celestial equator intersects the ecliptic. The axial wobble causes the celestial equator to change its position, and this causes the orbital positions of the equinoxes to change. The result is that the orbital positions of the Earth at the equinoxes move westward by 50.27″ (arcseconds) every year and complete a circuit of the ecliptic in about 25,800 years (360° ÷ 50.27″ = 25,800).

At present, Earth is at perihelion in early January and at aphelion in early June. In about 12,000 years, it will be at perihelion in June and at aphelion in January.

precipitation WATER that falls from the sky to the surface in either liquid or solid form is called precipitation, a word derived from the Latin *praecipitatio,* which means "I fall headlong." Precipitation physics is the branch of physical METEOROLOGY that is concerned with the physical processes that are involved in the formation of CLOUD DROPLETS, ICE CRYSTALS, and the resulting precipitation.

The average depth of the precipitation that falls during a specified time over a specified area is known as the depth-duration-area value (DDA value). The precipitation intensity is the amount of precipitation that falls to the surface within a specified period. It is measured in inches or millimeters per hour or day.

The zone of maximum precipitation is the elevation at which the precipitation that falls on a mountainside is greatest. Spillover is precipitation due to OROGRAPHIC lifting that is blown over the top of the mountain by the wind, so that it falls inside the area that is ordinarily in the rain shadow.

The probable maximum precipitation is an estimate of the greatest amount of precipitation that could conceivably fall on a given drainage area over a given period. It is calculated from records of the worst storms ever known in the area. The amount of precipitation is then converted into the amount of water that will flow through streams and rivers as a result. This figure is used to calculate the probable maximum flood, a figure that engineers use when designing dams. Although this calculation provides an estimate of the magnitude of the most severe flood, it does not calculate the probability that such a flood will occur within any stated period (such as 50 or 100 years).

Precipitable WATER VAPOR is the total amount of water vapor that is present in a column of air above a point on the surface of the Earth, or in a column of air within a layer of the atmosphere that is defined by the atmospheric pressure at its base and top. Precipitable water vapor is measured as the mass of water vapor in a unit area (such as pounds per square yard or kilograms per square meter). It is the amount of water that would fall as precipitation if all of it were to condense, but it is also the amount of water vapor that will react, as vapor, with outgoing radiation, thereby affecting the rate of atmospheric heating (*see* GREENHOUSE EFFECT). The proportion of the precipitable water that can fall as precipitation is known as the effective precipitable water.

When the relative HUMIDITY of the air exceeds 100 percent, water vapor will condense in the presence of CLOUD CONDENSATION NUCLEI to form cloud droplets or freeze in the presence of FREEZING NUCLEI to form ice crystals. Depending on the TEMPERATURE, the droplets or crystals then grow either by collision or by the Bergeron–Findeisen mechanism. They fall from the cloud when their weight exceeds the ability of vertical air currents to support them.

The effective precipitation is a value for the aridity of a climate that is important in many schemes for CLIMATE CLASSIFICATION, because the aridity of a climate determines its suitability for agriculture and the type of natural vegetation it will support. Aridity refers to the amount of water that is available to plants and it is equal to the difference between precipitation and EVAPORATION, or in other words to the effective precipitation. Effective precipitation is calculated as r/t, where r is the mean annual precipitation in millimeters and t is the mean annual temperature in °C. Precipitation that falls as SNOW must first be converted to its rainfall equivalent. If r/t is less than 40, the climate is considered to be arid, and if r/t is greater than 160, the climate is perhumid (extremely wet).

Between these extremes, the boundary between steppe grassland and desert, and the boundary between forest and steppe can be determined by values for r/t, depending how the precipitation is distributed. If precipitation falls mainly in winter, the two boundaries lie where $r/t = 1$ and $r/t = 2$, respectively. If precipitation is distributed evenly through the year, they fall where $r/(t + 7) = 1$ and $r/(t + 7) = 2$. If precipitation falls mainly in summer, they fall where $r/(t + 14) = 1$ and $r/(t + 14) = 2$.

The humidity coefficient is a measure of the effectiveness for plant growth of the precipitation falling over a region during a specified period. It relates the amount of precipitation to the temperature and is calculated as $P/1.07^t$, where P is the amount of precipitation in centimeters and t is the mean temperature for the period in question in degrees Celsius.

The moisture factor is also a measure of the effectiveness of precipitation. It is calculated by dividing the amount of precipitation in centimeters by the temperature in degrees Celsius for the period under consideration.

Water droplets, ice crystals, hailstones, and SNOWFLAKES that fall from clouds are called hydrometeors. Hydrometeors include drizzle, RAIN, freezing rain, HAIL, graupel, sleet, snow, and ice pellets. The fall of charged hydrometeors causes a downward flow of electric charge. This is known as a precipitation current. Meteoric water is water that falls from the sky as precipitation and then moves downward through the soil until it joins the GROUNDWATER (*see* JUVENILE WATER).

Not all precipitation falls from clouds. The term also includes DEW, white dew, hoar FROST, rime frost, glaze, FOG, and freezing fog. Precipitation that falls from a cloud but evaporates before reaching the ground is called virga (*see* CLOUD TYPES).

Precipitation that is wholly caused by the distribution of temperature and moisture within an AIR MASS and not to orographic lifting or the lifting of air in a frontal system (*see* FRONT), is called air mass precipitation.

Convectional precipitation results from thermal CONVECTION in moist air. The precipitation usually takes the form of rain, snow, or hail SHOWERS, which are sometimes heavy.

Precipitation that falls from clouds associated with a weather front is called frontal precipitation. Cyclonic rain is associated with a CYCLONE or DEPRESSION. Steady, persistent rain or snow falls from stratiform clouds along the warm front and cumuliform clouds along the cold front produce showers, which are sometimes heavy.

Mist is liquid precipitation in which the droplets are 0.0002–0.002 inch (0.005–0.05 mm) in diameter. These are large enough to be felt on the face of a person walking slowly through the mist. VISIBILITY in mist is greater than 1,094 yards (1 km). Mist is usually associated with stratus cloud. If the droplets increase in size, mist becomes drizzle.

Drizzle is liquid precipitation in which the droplets are smaller than 0.02 inch (0.5 mm) in diameter, are all of approximately similar size, and are very close together. They form by the coalescence of smaller droplets near the base of stratus cloud. As soon as a sufficient number have coalesced to reach a size that is just heavy enough to fall, droplets start to sink slowly. There are no upcurrents in stratus, so the droplets have no opportunity to coalesce to a larger size before they leave the CLOUD BASE and the base is low enough for them to reach the surface before evaporating.

Freezing drizzle is drizzle made of supercooled droplets (*see* SUPERCOOLING) that freeze on contact with the ground. Inside the stratus cloud from which the precipitation falls, the temperature is a little above freezing. Droplets falling through the cloud do not freeze, but when they leave the base of the cloud, their temperature is close to freezing. If the air temperature between the cloud base and the ground is below freezing, the droplets are chilled further as they fall, but because the cloud base is low they do not remain airborne long enough to freeze. Instead, they freeze immediately on contact with the ground, the temperature of which is also below freezing.

Freezing rain forms in the same way as freezing drizzle. Supercooled raindrops fall quickly from the cloud and are not exposed to the cold air long enough to freeze, but when they strike the ground they freeze on contact. Other types of frozen precipitation include freezing fog, frozen fog, frost smoke, graupel, hail, sleet, and snow.

Ice pellets are ice particles that are transparent or translucent, spherical or irregular in shape, and less than 0.2 inch (5 mm) in diameter. They are snowflakes that have partly melted and then refrozen, frozen raindrops or drizzle droplets, or SNOW PELLETS that are enclosed in a thin coating of ice.

Sleet consists of small raindrops that freeze in cold air beneath the base of the cloud in which they formed. They fall as small particles of ice of various shapes. Heavy sleet can reduce visibility. In Britain, sleet is a mixture of rain and snow falling together. All of it falls as snow from the base of the cloud and enters air that is below freezing temperature, but close to the ground there is a layer of warmer air in which some, but not all, of the snowflakes melt.

An outburst is a sudden, very heavy fall of precipitation from a cumuliform cloud that is caused by the strong downcurrents in the cloud. Outbursts often accompany THUNDERSTORMS.

Throughfall is the proportion of the total precipitation falling over a forest that reaches the ground. This consists of the sum of the amount that is not intercepted by plants and reaches the ground surface directly, the amount that drips from leaves, and the amount of STEM FLOW. It is equal to the total amount of precipitation minus the amount lost by evaporation from plant surfaces.

present weather Current weather conditions are included in a report from a weather station. Known as "present weather," these are represented by a series of two-digit numbers, from 00 to 99. Most of the categories are listed below. Categories 30–39 and 40–49 are not given in detail to avoid repetition. The descriptions are also simplified from the official versions, which are worded very carefully to avoid ambiguity and are therefore not easy to understand. When the present weather is reported, the number that is used is the highest that is applicable to the situation. In the following descriptions "freezing" means freezing on impact:

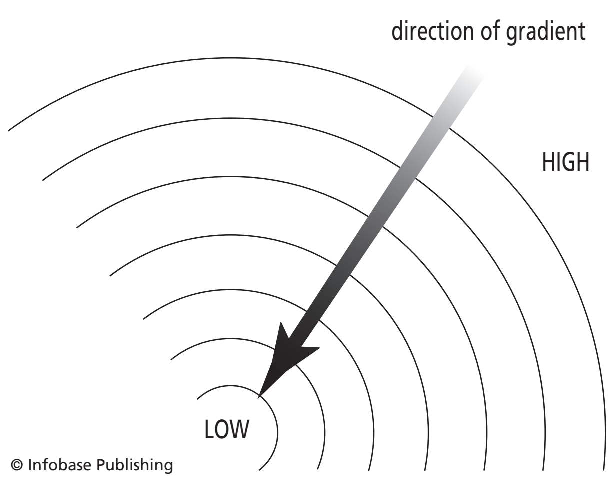
00 No cloud developing during the past hour
01 Cloud dissolving during the past hour
02 Cloud generally unchanged during the past hour
03 Cloud developing during the past hour
04 Visibility reduced by smoke
05 Haze
06 Dust widespread
07 Dust or sand raised by local wind, but not by dust storms, sandstorms, or whirls (devils)
08 Dust or sand whirls seen in the past hour, but no dust storms or sandstorms
09 Dust storm or sandstorm seen nearby during the past hour
10 Mist
11 Shallow, patchy fog or ice fog
12 Shallow continuous fog or ice fog
13 Lightning but no thunder
14 Precipitation seen, but not reaching the surface
15 Precipitation seen reaching the surface in the distance
16 Precipitation seen reaching the surface nearby, but not at the station
17 Thunderstorm but no precipitation seen
18 Squalls at the time of observation or during the past hour
19 Funnel cloud seen at the time of observation or during the past hour
20 Precipitation, fog, or thunderstorm during the past hour but not at the time of observation
21 Drizzle (not freezing) or snow grains, but not in showers
22 Rain (not freezing), but not in showers
23 Rain and snow or ice pellets, but not in showers
24 Freezing drizzle or freezing rain
25 Rain showers
26 Showers of rain and snow (British sleet) or snow
27 Showers of hail and rain or hail
28 Fog or ice fog in the past hour
29 Thunderstorm
30–39 Dust storms, sandstorms, drifting snow, or blowing snow
40–49 Fog or ice fog at the time of observation
50 Drizzle (not freezing) that is intermittent and slight at the time of observation
51 Drizzle (not freezing) that is continuous at the time of observation
52 Drizzle (not freezing) that is intermittent and moderate at the time of observation
53 Drizzle (not freezing) that is continuous and moderate at the time of observation
54 Drizzle (not freezing) that is intermittent and heavy at the time of observation
55 Drizzle (not freezing) that is continuous and heavy at the time of observation
56 Slight freezing drizzle
57 Moderate or heavy freezing drizzle
58 Slight drizzle and rain
59 Moderate or heavy drizzle and rain
60–69 The same as 50–59, but with rain instead of drizzle and in 58 and 59 snow instead of rain
70 Snowflakes, intermittent and slight at the time of observation
71–75 The same as 51–55, but with snow instead of drizzle
76 Ice prisms with or without fog
77 Snow grains with or without fog
78 Isolated, starlike, snow crystals with or without fog
79 Ice pellets
80 Rain showers, slight
81 Rain showers, moderate or heavy
82 Rain showers, violent
83 Rain and snow showers, slight
84 Rain and snow showers, moderate or heavy
85 Snow showers, slight
86 Snow showers, moderate or heavy
87 Slight showers of snow pellets, encased in ice or not, with or without rain or rain and snow (British sleet) showers
88 Moderate showers of snow pellets, encased in ice or not, with or without rain or rain and snow (British sleet) showers
89 Slight hail showers, without thunder, with or without rain or rain and snow (British sleet)
90 Moderate or heavy hail showers, without thunder, with or without rain or rain and snow (British sleet)
91 Slight rain
92 Moderate or heavy rain
93 Slight snow, or rain and snow (British sleet), or hail
94 Moderate or heavy snow, or rain and snow (British sleet), or hail
95 Slight or moderate storm with rain and/or snow, but no hail

96 Slight or moderate storm with hail
97 Heavy storm with rain and/or snow, but no hail
98 Storm with sandstorm or dust storm
99 Heavy storm with hail

pressure gradient (**isobaric slope**) Atmospheric pressure changes over a horizontal distance and the rate of change constitutes a gradient of pressure, or pressure gradient. The isobars (*see* ISO-) that join points of equal pressure on a surface resemble the contour lines on a physical map, and a line drawn at right angles to them shows the direction of the gradient, or slope, that inclines from a region of high pressure to one of low pressure.

The distance between isobars indicates the steepness of the gradient, just as does the distance between contour lines. That distance is proportional to the difference in pressure between the high and low regions, just as the distance between contour lines is proportional to the elevation of high and low areas of ground. Air moves because there is a pressure gradient, but it does not move directly down the gradient (*see also* gradient wind).

In synoptic METEOROLOGY, an increase in the pressure gradient that takes place over hours or days, leading to a strengthening of the winds, is called intensification. Weakening is a decrease in the pressure gradient that takes place over hours or days, causing a reduction in WIND SPEED.



The rate at which air pressure changes between centers of high and low pressure varies according to the distance between the centers and the intensity of the high and low pressure. The rate of change therefore constitutes a gradient, like the slope of a hillside, with the high pressure at the top of the hill and low pressure in the valley. The isobars resemble contours.

The area between two centers of high or low pressure where the pressure gradient is low is called a col. A col is the region of highest pressure between two CYCLONES and of lowest pressure between two ANTICYCLONES. On a constant-pressure (*see* WEATHER MAP) chart a col is shaped like a saddle.

pressure gradient force (**PGF**) It is the pressure gradient force that accelerates air horizontally across the surface of the Earth. It is produced by the PRESSURE GRADIENT, and its magnitude is proportional to the steepness of the gradient. The PGF has both vertical and horizontal components, but the vertical component, which tends to make the air rise, is balanced by the force of gravity and therefore can be ignored.

The pressure-gradient force always acts in the same direction as the pressure gradient. Consequently, that is the direction in which it tends to move the air—by the most direct route from a region of high pressure to a region of low pressure until the two are equal and the pressure gradient disappears. This is not what happens in fact, however, because of the CORIOLIS EFFECT, but it is the direction in which the PGF acts.

A force that continues to act causes the body on which it acts to accelerate, so the PGF is a force of ACCELERATION. Its magnitude can be calculated provided the relevant factors are known. These are the air DENSITY, the distance between the two points over which the PGF is being calculated, and the difference between the pressures at those two points. These values must be in compatible SI units (*see* APPENDIX VIII: SI UNITS AND CONVERSIONS). Distances must be converted to meters and pressures from millibars to pascals (1 mb = 100 Pa, *see* UNITS OF MEASUREMENT). One pascal is the pressure that will impart an acceleration of 1 meter per second per second, per kilogram, per square meter. The equation is:

$$F_{PG} = (1 \div d) \times (\Delta_p \div \Delta_n)$$

where F_{PG} is the PGF, d is the density of the air (in kilograms per cubic meter), Δ_p is the difference in pressure (in pascals), and Δ_n is the distance between the two places (in meters).

Suppose the sea-level air pressure is 1004 mb at Boston and 980 mb at New York, about 200 miles away.

$$1004 \text{ mb} = 100{,}400 \text{ Pa};$$

$$980 \text{ mb} = 98{,}000 \text{ Pa};$$

Δ_n (distance of 200 miles) = 321,800 m;

d (density of air) at sea level = approximately 1 kg/m^3;

Δ_p (pressure difference) = 100,400 - 98,000 Pa = 2,400 Pa.

Applying the equation:

$$F_{PG} = (1 \div 1) \times (2{,}400 \div 321{,}800) = 0.00746 \text{ m/s}^2$$

This is a very small acceleration, but it applies to only one kilogram of air, the mass of air that occupies one cubic meter, and it is an acceleration, not a speed. Although the sea-level air density is 1 kg/m^3, so the first term in the equation is 1 ÷ 1, the PGF is usually measured at some height above sea level, where the density of air is lower and the first term does not cancel.

pressure system An atmospheric feature that is characterized by AIR PRESSURE. The term is usually applied to a CYCLONE or ANTICYCLONE, but it may also refer to a RIDGE or TROUGH.

If a pressure system is embedded in the general westerly airflow of middle latitudes, the entire pressure system will travel from west to east. Such a pressure system is said to be migratory.

Program for Regional Observing and Forecasting Services (PROFS) A program that began in 1980–81 under the auspices of the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA). Its aim was to test and apply new scientific knowledge and technological innovations in order to improve operational weather services. The program was later renamed the Forecast Systems Laboratory (FSL). The FSL is now called the GLOBAL SYSTEMS DIVISION (GSD) of the Earth System Research Laboratory (ESRL).

Proterozoic The immensely long eon of the Earth's history in which multicellular organisms first appeared. The eon began 2,500 million years ago and ended 542 million years ago.

PLATE TECTONICS became the dominant force in shaping the Earth's crust, and by the middle of the Proterozoic, approximately 1,100 million years ago, all the continents were joined together to form a supercontinent called Rodinia. By about 900 million years ago Rodinia was starting to break apart. *See* APPENDIX V: GEOLOGIC TIMESCALE.

proxy data Climatologists cannot rely wholly on direct measurements of the state of the atmosphere in order to build up a picture of climate, because such measurements may not exist. The scientists are not left helpless, however, because there are other measurements that do not refer to the climate directly, but which can be interpreted to yield information about climate. These are called proxy data.

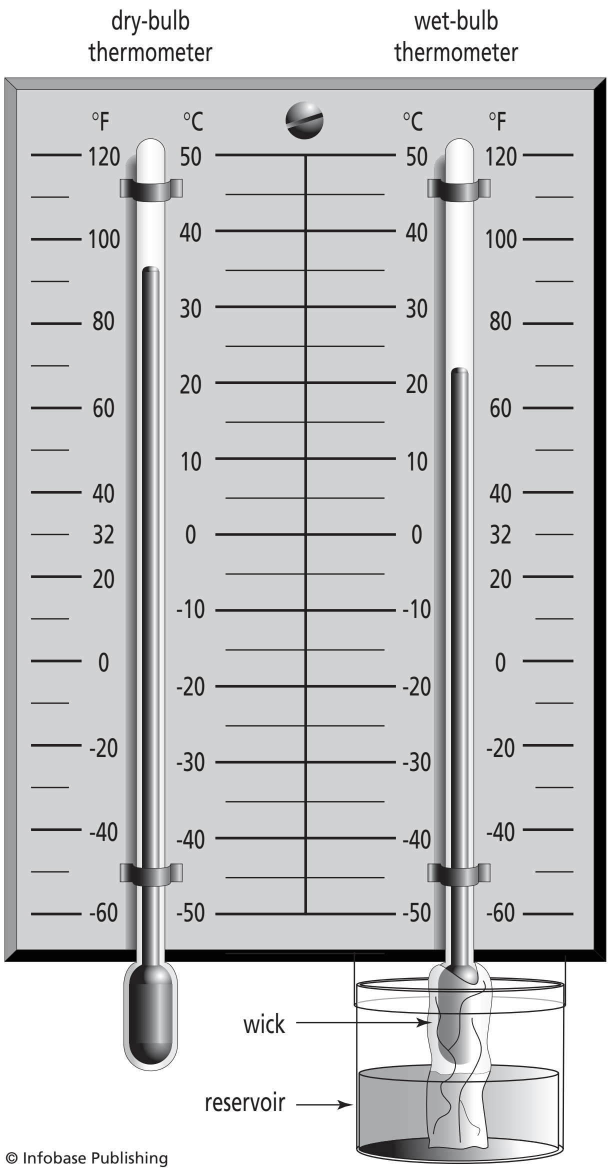
TREE RINGS, ICE CORES, POLLEN, and animal remains (*see* BEETLE ANALYSIS) are among the sources of proxy data. Proxy data is the only data available for the reconstruction of prehistoric climates.

psychrometry The Greek word *psukhros* means "cold" and *metron* means "measure," so psychrometry is literally the measurement of coldness. In fact, psychrometry is the operation of calculating the relative HUMIDITY and DEW point TEMPERATURE from the extent to which the reading given by a THERMOMETER with a bulb that is kept wet is lower than the reading from a thermometer with a dry bulb. In other words, the calculation is based on a measurement of the coldness of the wet-bulb thermometer. The instrument used to make the measurement is a type of HYGROMETER called a psychrometer.

A psychrometer comprises two thermometers mounted parallel to each other and held a short distance apart. One, known as the dry-bulb thermometer, measures the air temperature. The other, known as the wet-bulb thermometer, indirectly measures the rate of EVAPORATION. The bulb of this thermometer is wrapped in a wick, usually made from muslin, which is partly immersed in a reservoir of distilled water.

Water is drawn by CAPILLARITY into the wick from where it evaporates. The LATENT HEAT of vaporization is taken from the thermometer bulb, thus depressing its temperature. The rate at which water evaporates, and therefore the amount of latent heat supplied by the bulb, varies according to the relative humidity of the air.

To ensure an accurate reading, it is necessary to provide a flow of air over the thermometers and to ensure that the wick remains wet at all times, but is not allowed to become sodden. If the wick is sodden, water will evaporate from its surface, but the layer of wick in contact with the bulb will remain unaffected. Neither relative humidity nor the dew point temperature can be



A psychrometer is an instrument for measuring wet-bulb and dry-bulb temperatures. Two identical thermometers are mounted side by side on a board. The wet bulb is wrapped in a wick that is partly immersed in a reservoir of distilled water.

read directly from the instrument, but both can be calculated from its readings.

An aspirated hygrometer is a psychrometer in which the necessary flow of air over the thermometers is provided by placing them inside a tube through which air is blown.

A whirling psychrometer is swung through the air to ensure an evenly distributed flow of air over both bulbs. This process increases the accuracy of the instrument.

In a whirling psychrometer, also called a sling psychrometer, the flow of air across the bulbs of the dry-bulb and wet-bulb thermometers is produced by manually whirling the instrument through the air. In one version, a chain is attached at the top of the board to which both thermometers are securely fixed and there is a handle on the other end of the chain. In another version, the board forms the horizontal arm of a device resembling a rattle. The top of the board is fixed to a rod, one end of which is attached to a handle in which it is free to rotate.

Q

quasi-biennial oscillation (QBO) An alternation of easterly and westerly winds that occurs in the stratosphere (*see* ATMOSPHERIC STRUCTURE) above the TROPICS, between about 20°S and 20°N. The change happens on average every 27 months, but the period varies from less than two years to more than three years.

Easterly winds become established at a height of about 12 miles (20 km) usually between about May and September. Then westerly winds in the upper stratosphere, above about 19 miles (30 km), begin to extend downward until by about January westerlies predominate.

The QBO causes a meridional circulation (*see* GENERAL CIRCULATION) that affects the distribution of traces gases, including OZONE, in the stratosphere over the Tropics and subtropics, and some scientists suspect that in winter the QBO may be linked to the arctic polar VORTEX and to sudden periods of warm weather. This happens because sudden warming in high latitudes is associated with ROSSBY WAVES that start in the troposphere and propagate upward into the stratosphere. Rossby waves are able to propagate in this way if the stratospheric winds are westerlies, but not if they are easterlies.

KELVIN WAVES are also influenced by the QBO. The severity of winters in the Northern Hemisphere is linked to both the QBO and the SUNSPOT cycle. Winters are generally warmer when the stratospheric winds are westerlies than they are when the winds are easterlies. The phase of the QBO affects the frequency and intensity of Atlantic and Pacific TROPICAL CYCLONES, and the QBO is one of the factors influencing the MONSOON. It also affects rainfall patterns in the SAHEL.

Scientists do not fully understand the QBO or the ways in which it affects the weather, however.

Further Reading

Heaps, Andrew, William Lahoz, and Alan O'Neill. "The Quasi-Biennial zonal wind Oscillation (QBO)." University of Reading. Available online. URL: http://ugamp.nerc.ac.uk/hot/ajh/qbo.htm. Accessed January 24, 2006.

Quaternary The Quaternary sub-era of the Earth's history began approximately 1.81 million years ago and continues to the present day. Although the name is still widely used, it is likely to be dropped from formal use within the next few years. The Quaternary sub-era covers the same span of time as the PLEISTOGENE period. *See* APPENDIX V: GEOLOGIC TIMESCALE.

QuikScat A NASA satellite that was launched on June 19, 1999, from Vandenberg Air Force Base, California, on a Titan II rocket of the U.S. Air Force. It entered an elliptical orbit at a height of about 500 miles (800 km).

QuickScat, short for Quick Scatterometer, replaced the NASA Scatterometer (NSCAT) that was lost in June 1997, when the satellite carrying it lost power. It carries the SEAWINDS RADAR instrument.

R

radar An electromagnetic device that is used to detect and measure the direction, distance, and motion of objects that are otherwise invisible due to darkness or because they are obscured by a medium the radar can penetrate. The name is from "*ra*dio *d*etection *a*nd *r*anging."

Radar devices transmit an electromagnetic wave as a beam from an antenna. If the beam is interrupted by striking an object, a part of it is reflected and the device receives the reflection. Information is obtained by comparing the signal and its reflection.

Electromagnetic waves travel at the speed of light, so the time that elapses between the transmission and the reception of its reflection indicates the distance to the object (about 500 feet (150 m) for every microsecond of delay). This type of measurement is made by pulse radar, in which short, intense bursts of radiation are transmitted, with a fairly long interval between bursts. Continuous-wave radar transmits a continuous beam. In its basic form, continuous-wave radar cannot be used to measure distance, but it can measure the speed at which the target object is moving, as the DOPPLER EFFECT. Frequency-modulated radar is a more advanced version of continuous-wave radar that can measure distance, because each part of the signal is tagged to make both it and its reflection recognizable.

A cloud echo is a radar signal that is reflected by CLOUD DROPLETS. The wavelength (*see* WAVE CHARACTERISTICS) of the radar transmission determines the size of the objects that will reflect it. The longer the wavelength, the bigger the objects it will detect. Consequently, very short-wave radar beams are used to detect cloud droplets, which are extremely small. It is not possible to tell from a cloud echo whether the cloud is producing PRECIPITATION.

If the cloud is producing precipitation, the radar echo will produce a precipitation echo, which is a characteristic image on the radar screen. A precipitation cell is an area indicated by radar within which precipitation is fairly continuous. A spiral band is a pattern on a radar screen made by echoes from the center of a TROPICAL CYCLONE. The radar reflections are from areas of heavy rainfall, and the pattern forms a roughly spiral shape that curves inward toward the storm center and merges in the wall cloud (*see* CLOUD TYPES).

A bright band is an enhanced radar echo that is seen in an image of a cloud where SNOWFLAKES are melting into RAINDROPS. The melting band is a region in certain clouds, especially nimbostratus, where melting snowflakes become coated in a layer of water. The snow then reflects radar waves more strongly than the ICE CRYSTALS and SNOWFLAKES above or the raindrops below, so the region appears on radar screens as a bright, horizontal band. The existence of melting bands confirms that in middle and high latitudes most of the rain that reaches the ground is melted snow. The height at which melting bands occur is known as the melting level. It is the level at which the temperature is slightly above freezing, so that falling ice crystals and snowflakes begin to melt.

A blob is a signal on a radar screen that indicates a small-scale difference in TEMPERATURE and HUMIDITY.

It is produced by atmospheric turbulence (*see* TURBULENT FLOW).

A wind that is observed by radar is called a radar wind. The radar tracks a radiosonde WEATHER BALLOON or a balloon carrying a radar reflector in order to determine the speed and direction of the wind at a particular height. Knowing the distance to the target from the time lapse between transmission and echo and its angle of elevation allows the height of the balloon or reflector to be calculated by trigonometry.

Doppler radar uses two radar devices to measure the Doppler effect on water droplets and, from that, to determine the speed at which the droplets are rotating about a vertical axis. Doppler radar is employed to study air movements and measure the wind speed inside TORNADOES.

WEATHER RADAR is widely used in the study of clouds, precipitation, and storms. A tornado funnel is visible because WATER VAPOR condenses in the low atmospheric pressure prevailing inside the funnel, producing water droplets that are detectable by radar. The funnel also extends upward, through the wall cloud and into the MESOCYCLONE. These regions cannot be seen, because they are surrounded by cloud that obscures them, but they are visible to radar, allowing the entire structure of a tornadic storm to be examined.

If two radar transmitters are set some distance apart horizontally, the two beams they transmit will enter the cloud at different points. If there is a horizontal component to the movement of water droplets at these points toward or away from the transmitter, there will be a measurable Doppler effect on the reflected beams. This will reveal whether the air inside the cloud is rotating, because if it is rotating the reflection from one side of the center of rotation will be red-shifted and that from the other side will be blue-shifted. If the air is rotating, the extent of the red and blue shifts will indicate the speed of rotation.

The Doppler radar devices used to study tornadoes and other severe storms produce real-time color displays, allowing storms to be studied and measured while they are still active. This has made it possible to issue increasingly accurate severe storm and tornado warnings.

The use of Doppler radar for meteorological research was developed during the 1970s, principally at the National Severe Storms Laboratory, at Norman, Oklahoma. Its first success was in 1973, with the study of a SUPERCELL storm at Union City, Oklahoma. It was by means of Doppler radar that meteorologists discovered the way a mesocyclone forms high in the storm cloud and then extends downward shortly before a tornado emerges beneath the cloud. A device called Doppler on Wheels (DOW), developed by a team led by Joshua Wurman at the Center for Severe Weather Research, was first deployed in 1995; since then it has collected data on approximately 100 tornadoes, as well as eight tropical cyclones and several forest fires. On May 3, 1999, DOW also measured the fastest wind speed ever recorded, of 301 MPH (484 km/h) near ground level in an Oklahoma tornado. Most Doppler radars transmit a single beam and take about five minutes to complete a vertical and horizontal scan of a tornadic storm. Rapid-Scan Doppler on Wheels, also developed by the Wurman team and capable of scanning a tornadic storm at 5–10 second intervals, was deployed in 2005.

Until Doppler radar became available, there was no way to measure the wind speed around the center of a tornado accurately. People guessed at the speeds, and some scientists suggested the winds might occasionally reach or even exceed the speed of sound. At 68°F (20°C) this is about 770 MPH (1,239 km/h). The radar detected winds approaching 300 MPH (483 km/h) and meteorologists now believe this is close to the highest speed they ever reach.

These successes led to the establishment of the Joint Doppler Operational Project (JDOP), based at Norman, Oklahoma, which ran from 1976 until 1979. This led in turn to the NEXT GENERATION WEATHER RADAR program, which began in 1980.

Portable Doppler radars are sometimes used to study tornadoes. These can be set up within a few miles of a tornado. They transmit at a relatively short wavelength. This allows them to emit a narrow beam with a resolution high enough to measure conditions at different parts of the storm, and therefore wind speeds, but their reflections can sometimes be difficult to interpret. Bigger radars study storms from a distance of 100 miles (160 km) or more, but at long distances the curvature of the Earth places the lowest part of a storm below the horizon and out of the reach of a radar beam. Two sets of Doppler radars are used to study storms forming along SQUALL lines, where the storms themselves are moving across the field of view.

Radar will also scan solid surfaces. Radar altimetry is a technique for measuring the topography of a land surface by means of a radar ALTIMETER carried by an aircraft or space vehicle. The altimeter measures the distance between the vehicle carrying it and the surface vertically below it. Provided the vehicle remains at a constant height in relation to a DATUM level (not the ground surface), its distance to the surface will vary according to changes in the ground elevation. With a series of passes the physical features of the landscape can be measured and plotted, and the plots used to compile a map.

Radar interferometry is used to measure very small changes in the shape of features on the solid surface of the Earth. These can give warning of an impending volcanic eruption. An instrument called an interferometer mounted on an observational satellite transmits radar waves that interact with each other to produce characteristic patterns known as interference fringes. The appearance of the fringes varies with very small changes in the distance traveled by the radar pulse and its echo.

Synthetic aperture radar (SAR) is a type of radar in which the instrument moves on board an aircraft or satellite. The SAR transmits a continuous-wave signal at a precisely controlled frequency, so the signal is coherent, and it stores the reflected signals in a memory. This allows it to process a large number of echoes at a time. The effect is similar to that of an instrument with a large antenna, although only a small antenna is used. SAR is used to map the surface of Earth or other planets in great detail.

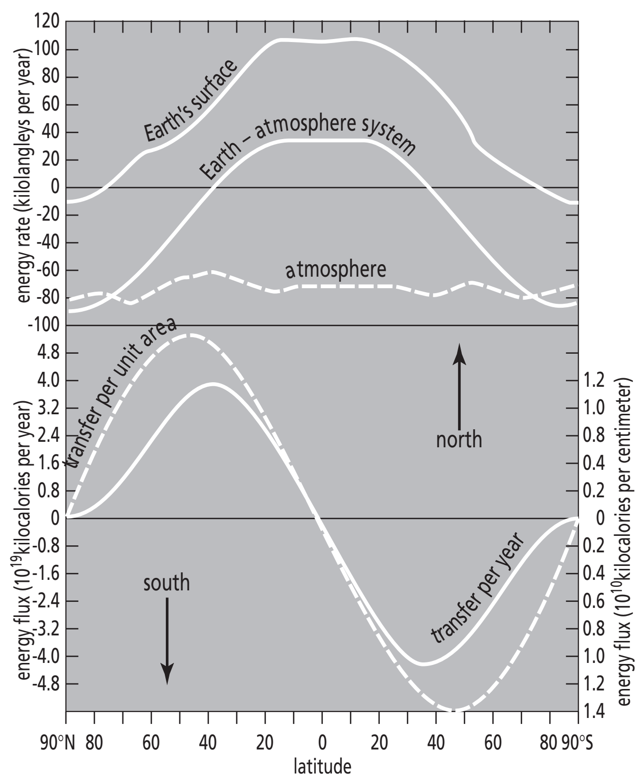
radiation balance When the amount of energy that the Earth receives from the Sun is compared to the amount that is reflected and radiated from the Earth into space, the difference between incoming and outgoing radiation represents a radiation balance. This is the energy budget of the Earth, in which the amount of energy the Earth receives from the Sun is set against the way that energy is distributed and eventually returned by radiating it back into space. It can be summarized as:

$$R = (Q + q)(1 - a) - I$$

where R is the radiation balance, Q is the direct sunlight reaching the surface, q is the diffuse sunlight reaching the surface, a is the ALBEDO of the surface, and I is the outgoing long-wave radiation from the surface. On average, the surface of the Earth absorbs about 124 kly (kilolangleys, *see* UNITS OF MEASUREMENT) of radiation each year and radiates about 52 kly into space. This means that the surface absorbs 72 kly more than it radiates.

The same equation can also be applied to the atmosphere. It absorbs about 45 kly of energy a year and radiates about 117 kly into space. The atmosphere therefore radiates 72 kly more than it absorbs. Consequently, the figures for the surface and atmosphere are in balance over the year. If this were not the case, the world would be growing either warmer or cooler (but *see* GLOBAL WARMING).

The balance is achieved by the transfer of energy from the surface to the atmosphere. Some of this transfer occurs directly. As the surface is warmed by the Sun, the air in contact with it is also warmed by CONDUCTION, and its warmth is transferred upwards by CONVECTION. Most of the transfer is due to the EVAPORATION of water from the surface and its CONDENSATION in the atmosphere. Evaporation absorbs LATENT



The upper section of the graph shows the distribution of solar energy per year for the surface of the Earth, the atmosphere, and the surface and atmosphere considered together. The lower section shows the horizontal transfer of energy from low to high latitudes.

HEAT from the surface and condensation releases latent heat into the air.

Solar energy is not received equally in all areas of the Earth. The Sun shines more intensely on the equator than it does on the poles. The resulting difference in available energy increases with latitude. This is because in latitudes higher than 40°, the atmosphere loses more energy in a year than the surplus that is absorbed by the surface, and in latitudes lower than 40° the reverse is true and the surface absorbs more energy than the atmosphere loses. Despite this, the poles do not grow colder year by year, nor the TROPICS warmer. The balance is maintained by the horizontal transfer of heat. Without that transfer the radiation budget would balance at each latitude only if the mean temperature at the equator were 25°F (14°C) higher than it is and the mean temperature at the poles 45°F (25°C) lower.

Ocean currents (*see* GYRES) and the GENERAL CIRCULATION of the atmosphere transfer heat away from the equator. ADVECTION through the atmosphere accounts for a little more than half of the total transfer. Evaporation and condensation also increase the rate of this horizontal transfer of heat from low to high latitudes.

The total amount of annual heat transfer reaches a maximum at about latitudes 40°N and S. The maximum amount per unit area of the surface is transferred at about 45°N and S. It is slightly greater in the Southern Hemisphere than in the Northern Hemisphere. Much of the transfer in the Tropics and subtropics occurs in the upper troposphere (*see* ATMOSPHERIC STRUCTURE) through the Hadley cell circulation. The transfer in middle latitudes occurs mainly through the CYCLONES and frontal systems (*see* FRONT) that move with the prevailing westerlies (*see* WIND SYSTEMS). The rate of meridional transport varies with the temperature gradient. The gradient is steepest in winter, and that is when the atmospheric circulation is most vigorous.

radiation cooling At night the Earth's surface radiates heat, thereby reducing the surface temperature. This is radiation cooling.

During the day the Earth's surface absorbs solar radiation. Some of the absorbed radiation is in the form of heat, and absorbed light (*see* SOLAR SPECTRUM) is converted to heat. As heat absorption causes its temperature to rise, the surface also emits infrared radiation (*see* BLACKBODY). The amount of energy radiated in this way is proportional to the temperature of the surface (*see* STEFAN-BOLTZMANN LAW), but during the day it is always less than the amount of solar radiation that is being absorbed. Consequently, the surface temperature rises through the day, reaching a peak in the middle of the afternoon. At night the blackbody radiation from the surface continues, but the absorption of solar radiation ceases. Consequently, there is a net loss of energy from the surface and therefore the surface cools. Its temperature continues to fall through the night, then starts rising again at dawn.

Most of the blackbody infrared radiation is absorbed by gases in the atmosphere (*see* GREENHOUSE EFFECT). These then reradiate it. On clear nights atmospheric absorption occurs throughout the troposphere (*see* ATMOSPHERIC STRUCTURE). It warms the air, but allows the ground surface to cool. On cloudy nights the clouds form a barrier to the radiation. They reflect some of it and absorb some of it, reradiating a proportion of it downward. This greatly reduces the rate at which the surface cools and explains why in spring and fall frosts are more likely on clear nights than on cloudy nights.

A night when the sky is clear is known as a radiation night. The absence of cloud allows the surface to cool rapidly. The drop in temperature close to the ground is especially marked when the air is still, because air movements would mix warmer air with the cold air at ground level.

radiative dissipation When fingers of warm air penetrate cooler air, they cool by radiating away, or dissipating, their surplus heat. This is radiative dissipation.

While the air is at a higher temperature than its surroundings, the temperature difference represents available POTENTIAL ENERGY that could be converted into KINETIC ENERGY. By radiating its heat, however, the available potential energy is dissipated before it can be converted.

radioactive decay Unstable atomic nuclei lose elementary particles and continue to lose them until the nuclei become stable. This represents the decay of those nuclei. ISOTOPES of chemical elements that have nuclei subject to this type of decay are said to be radioactive, since the decay results from the emission of electromagnetic radiation and the loss of particles. It is radioactive decay.

For example, naturally occurring uranium (U) is a mixture of three isotopes. ^{238}U accounts for 99.28 percent of the total mass, ^{235}U for 0.71 percent, and ^{234}U for 0.006 percent. All three isotopes are radioactive. ^{234}U and ^{238}U both decay in the same way and eventually become ^{206}Pb (lead-206), which is stable. ^{238}U has a HALF-LIFE of 4,510 million years and the half-life of ^{234}U is 2.48 million years. These isotopes undergo ALPHA DECAY eight times and BETA DECAY six times. ^{235}U, with a half-life of 713 million years, undergoes seven alpha decay steps and four beta decay steps, and finally it also becomes a stable isotope of lead, ^{207}Pb.

It is impossible to predict when an individual nucleus will undergo decay, but the rate at which a particular isotope decays is very constant and can be used to determine the half-life for that isotope. The constancy of radioactive decay means it can be used for RADIOMETRIC DATING, the best known version of which is RADIOCARBON DATING.

radiocarbon dating A method that exploits the regularity of RADIOACTIVE DECAY to calculate the age of a sample taken from what was once a living organism by measuring the proportions of two carbon ISOTOPES that the sample contains. The two ISOTOPES are carbon-12 (^{12}C) and carbon-14 (^{14}C).

^{12}C is the stable isotope. ^{14}C is formed in the atmosphere by the action of COSMIC RADIATION on nitrogen (^{14}N). Cosmic radiation bombards the air with neutrons. Occasionally a neutron strikes the nucleus of a nitrogen atom and replaces one of its protons. That replacement leaves the mass of the atom unchanged, but alters it from $^{14}_{7}N$ to $^{14}_{6}C$. The ^{14}C is then oxidized to carbon dioxide (CO_2).

Plants absorb CO_2 and incorporate its carbon in sugars by the process of PHOTOSYNTHESIS. The plants do not discriminate between ^{12}C and ^{14}C, so the two isotopes are present in plants in the same proportion as they are in the atmosphere. The carbon then passes to animals that eat the plants and their bodies also contain both isotopes.

^{14}C is unstable and undergoes radioactive decay with a HALF-LIFE of 5,730 years. While the plant or animal is alive, the ^{14}C in its tissues is constantly being replenished, but after its death the organism ceases to absorb carbon and replenishment ceases. The ^{14}C continues to decay at a steady and known rate. This alters the ratio of ^{14}C:^{12}C. Measuring the ratio in the sample and comparing it to that in the atmosphere therefore make it possible to calculate the time that has elapsed since the organism died. Obviously the technique can be used only with material that once formed part of a living organism. It can date wood, linen, cotton, wool, hair, or bone, but not stone or metal.

When the technique was first introduced in the late 1940s by the American chemist Willard Frank Libby (1908–80) the half-life of ^{14}C was thought to be 5,568 years. The year 1950 was set as the base (the "present") against which ages were to be reported. That date was chosen because it was about then that the atmospheric testing of nuclear weapons altered the ^{14}C:^{12}C ratio. Before long, material was being examined and then dated as having been formed so many years BP (before the present). Some years later the ^{14}C half-life was recalculated and all the previously announced dates had to be revised.

Then another difficulty was discovered. Radiocarbon dating was based on the assumption that the ratio of ^{14}C:^{12}C in the atmosphere had remained constant for tens of thousands of years. This is now known to be untrue. The ratio varies a little. This means that ages measured by radiocarbon dating do not correspond directly to historical ages. The variation is not constant, the extent of it fluctuating in an irregular fashion, which makes dating far from simple.

The difference can cause confusion. A human skeleton that was found in California in 2000 was reported as being 13,000 years old. At Monte Verde, a site in southern Chile, there are objects made by people and dated at 12,500 years. It sounds as though the California skeleton is older than the Monte Verde site, but this is not so. The California date was in calendar years, the Monte Verde date in radiocarbon years, and 12,500 radiocarbon years are equal to 14,700 calendar years.

It is important, therefore, to state what kind of years are being reported. Radiocarbon dates should always be described as "radiocarbon years" BP, or as "percent modern," which means the proportion of ^{14}C in the sample compared with that in samples that were formed in 1950, such as a piece of wood cut from a tree in that year.

Radiocarbon years are calibrated to convert them into calendar years. The calibration compares radiocarbon years and TREE RING years. The ^{14}C:^{12}C ratio is measured in the sample. Then a tree ring with a similar ratio is found by searching through published data. The age of the tree ring is known, and because it contains the same carbon isotope ratio the tree ring

Calendar and radiocarbon ages

Calendar	Radiocarbon
11	9.6
12	10.2
13	11.0
14	12.0
15	12.7
16	13.3
17	14.2
18	15.0
19	15.9
20	16.8

must be the same age as the sample. The calibrated age is then reported as CalBC, CalAD, or CalBP, to indicate whether the age is measured as B.C. (B.C.E.), A.D. (C.E.), or BP.

The table above compares some radiocarbon and calendar ages (in thousands of years).

Radiocarbon dating is widely used in paleoclimatology (*see* CLIMATOLOGY). It makes it possible for scientists to date plant material that they can link to particular climatic conditions.

Further Reading

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radiometric dating Any method that exploits the very regular rate of RADIOACTIVE DECAY in order to determine the age of rocks and organic material can be called radiometric dating. This regularity means that the proportions of parent (original, radioactive) and daughters (decay products) ISOTOPES present in the material can be used to calculate the time that has elapsed since the material was formed. At that time the material either contained the isotopes in different proportions, or contained only the parent isotope if the daughters are produced only by the decay of the parent.

Several elements are used in radiometric dating. Organic material that is thousands of years old can be dated by RADIOCARBON DATING. Other decay series are used to date rocks, which are much older. The first to be introduced was the decay of uranium (HALF-LIFE 4.51 billion years or 713 million years, depending on the isotope) to lead (Pb). ^{232}Th (thorium-232), with a half-life of 13.9 billion years, decays to ^{207}Pb and this decay is also used for dating.

Potassium (^{40}K) decays to argon (^{40}Ar) with a half-life of 1.5 billion years. Rubidium (^{87}Rb) decays to strontium (^{87}Sr) by a single BETA DECAY, but there is uncertainty about the half-life, which may be 48.8 billion years or 50 billion years. Samarium (^{147}Sm), with a half-life of 250 billion years, undergoes ALPHA DECAY to become neodymium (^{143}Nd). All of these decays are used to date rocks.

radon (Rn) A radioactive element that is one of the NOBLE GASES. Radon is colorless, tasteless, and odorless. It has atomic number 86, relative atomic mass 222, and its DENSITY is 0.09 ounces per cubic inch (0.97 g/cm^3). It melts at -95.8°F (-71°C) and boils at -79.24°F (-61.8°C).

Radon is formed by the RADIOACTIVE DECAY of radium-226 and undergoes ALPHA DECAY. There are at least 20 ISOTOPES of radon, the most stable of which is ^{222}Rn, which has a HALF-LIFE of 3.8 days.

Air contains very small but variable amounts of radon. Radium, the source of radon, is a rare metal that occurs mainly in granites. Consequently, the concentration of radon is highest where the underlying rock is granite.

As they decay, radon atoms ionize (*see* ION) nearby atoms of atmospheric gases. This process increases the electrical conductivity of air, but the effect is extremely small. Most radon decay products, called radon daughters, also emit alpha radiation. In large doses, radon and its daughters are known to cause lung cancer and so measures are taken to prevent the accumulation of radon inside buildings where the natural radon level is high.

rain Rain is liquid PRECIPITATION consisting of droplets that are between 0.02 inch and 0.2 inch (0.5–5.0 mm) in diameter. In heavy rain the droplets vary in size considerably. Small RAINDROPS are spherical, but those approaching 0.2 inch (5 mm) in size are variable in shape. Fine rain falls from nimbostratus and stratocumulus (*see* CLOUD TYPES) when the cloud base is low. Droplets more than about 0.4 inch (1 mm) in size require to fall through several thousand feet of cloud in order to grow to this size. These are usually associated with cumulus or cumulonimbus clouds and they fall as SHOWERS or in rainstorms.

Most raindrops are SNOWFLAKES that have melted in the lower part of the cloud or between the CLOUD BASE and the surface. Rain falling from a warm cloud—a cloud consisting entirely of liquid droplets, with no ICE CRYSTALS—is known as warm rain. Warm rain is at a higher temperature than rain that falls from cold clouds—consisting entirely of ice crystals—or mixed clouds—containing both ice crystals and liquid droplets.

Rain that contains a quantity of fine soil particles that are large enough to discolor the rainwater and leave a mudlike deposit on surfaces is called mud rain.

Rainfall frequency is a measure of how often rain falls in a particular place. This is of vital agricultural importance, and it also determines the type of natural vegetation a region supports. Two places may both receive the same amount of rain in the course of a year, but the place where rainfall is distributed evenly throughout the year will have a quite different type of natural vegetation from the place where all the rain falls in one short season. The number and distribution of rain days reveal the effectiveness of rainfall for agriculture and natural plant growth. Rainfall frequencies are also used to define RAINFALL REGIMES.

As the name suggests, a rain day is a day on which rain falls. This is usually taken to mean a period of 24 hours, beginning at 0900 Z (*see* UNIVERSAL TIME), during which at least 0.08 inch (0.2 mm) of rain falls. The number of rain days in one month and in one year indicate the distribution of rainfall through the year and provide a useful measure for comparing the climates of two places.

Seattle, Washington, for example, has an average of 51 rain days between April and September and 99 rain days between October and March, indicating that its climate is rainier in winter than in summer. Las Vegas, Nevada, on the other hand, is dry throughout the year, with no more than one or two rain days in each month and a total of 18 rain days in the year. Taken together, the number of rain days and total annual rainfall give a clear picture of the seasonality of a climate. Seattle receives a total of 33.4 inches (848 mm) of rain a year on 150 rain days. Mumbai, India, with a strongly seasonal MONSOON climate, receives 71.3 inches (1,811 mm) a year but has only 72.7 rain days. Dividing the amount of rainfall by the number of rain days gives an idea of the intensity of the rainfall.

A period each year when the amount of precipitation is much higher than it is at other times is known as a rainy season. The rainy season may occur in winter or in summer. Rainy winters occur around the Mediterranean Sea and on the western sides of continents in latitudes 30–45°N and S. San Francisco, California, receives an average 22 inches (561 mm) of rain a year, of which 21 inches (534 mm) fall between October and April. Gibraltar, at the southern tip of Spain, has a very similar climate. Its average annual rainfall is 30 inches (770 mm), of which 28 inches (711 mm) fall between October and April. In regions with a monsoon climate it is the summer that is wet. Mumbai receives an average 71.3 inches (1,811 mm) of rain a year. Of this total, 67 inches (1,707 mm) falls between June and September.

Zenithal rain is rain that falls every year, or every other year, during the season when the Sun is most nearly overhead—at its zenith. This type of rainfall distribution occurs in parts of the TROPICS and subtropics.

A hyetogram is a chart that records the amount and duration of rainfall at a particular place. Hyetography is the scientific study of the annual geographic distribution of precipitation and variations in it.

raindrops RAIN is PRECIPITATION that reaches the ground as drops of WATER larger than those of drizzle. The drops of water that fall from a cloud to reach the surface as rain vary in size, but there is a minimum size below which they are unable to survive their passage through the air below the CLOUD BASE.

Mist and FOG consist of droplets about 100 µm (0.004 inch) in diameter, but these are really very large CLOUD DROPLETS. They form near the surface, and they are too small to fall because air resistance and turbulence are sufficient to keep them aloft. Raindrops are at least about 1 mm (0.04 inch) across. The size limitation is due to the rate at which a drop of water falls in relation to the rate at which it evaporates.

The TERMINAL VELOCITY (*V*) of a drop of water falling through still air is equal to 8,000 times its radius ($V = 8 \times 10^3 r$), where *r* is the radius measured in SI units (*see* APPENDIX VIII: SI UNITS AND CONVERSIONS). A drop that is 1 mm (0.04 inch) in diameter therefore falls at about 4 m/s (157 inches per second). The base of a cloud marks the boundary between saturated and unsaturated air. If the base is at 60 m (200 feet), the drop will spend 15 seconds falling through the dry air. Suppose, though, that the drop is half that size. It will then spend 30 seconds in the dry air. If the air is turbulent, as it is inside cumuliform clouds (*see* CLOUD TYPES) and around drops that are very much bigger, the terminal velocity is much slower ($V = 250r^{1/2}$). A raindrop 5 mm (0.2 inch) across falls at about 0.4 m/s (16 inches per second) and would take 150 seconds to fall 60 m (200 ft).

The rate of EVAPORATION depends on the TEMPERATURE and relative HUMIDITY (RH) of the air beneath the cloud. RH is variable, but even if it is about 95 percent, so the air is almost saturated, a drop that is less than about 30 µm (0.0012 inch) will have evaporated completely by the time it has fallen a few inches. No drop smaller than about 100 µm (0.004 inch) in diameter is likely to reach the surface, because the base of most clouds is higher than 500 feet (150 m). That is the maximum distance such a drop can fall through air at 40°F (5°C) and RH 90 percent before it evaporates.

Bigger drops survive much better. A droplet 1 mm (0.04 inch) across can fall 42 km (26 miles) through air at this temperature and RH before it evaporates completely, and one 2.5 mm (0.1 inch) can fall 280 km (174 miles). In fact it is not possible for raindrops to fall this distance, because above about 7 miles (11 km) the air is too dry for drops to form.

Consequently, bigger drops reach the surface as raindrops. Typical raindrops are between 0.08 inch (2 mm) and 0.2 inch (5 mm) in diameter, and they fall at 14–20 MPH (23–33 km/h). Drops smaller than these that reach the ground are classed as drizzle. Raindrops larger than about 0.2 inch (5 mm) usually break apart into two or more smaller drops.

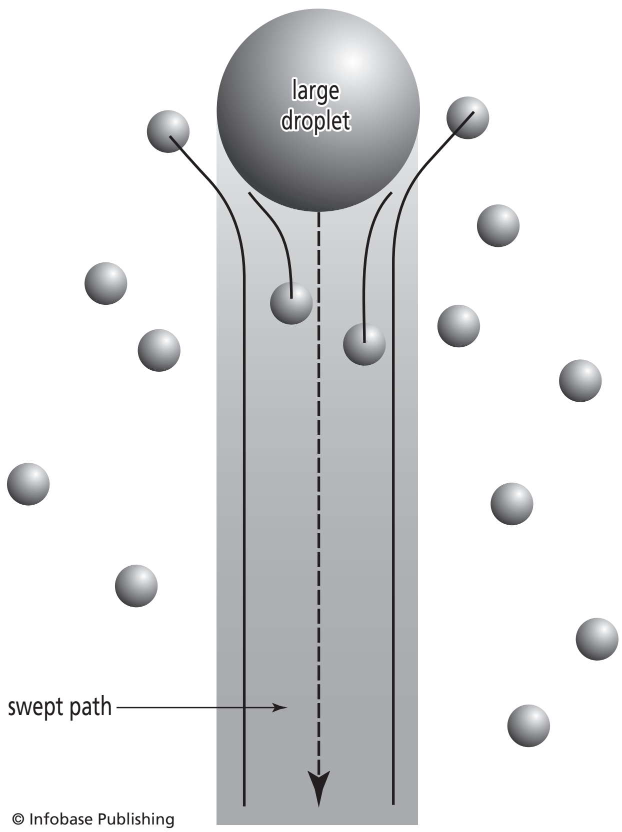
Raindrops form from cloud droplets. These are typically about 20 µm (0.0008 inch) across. Depending on the temperature inside the cloud, they grow by collision or by the Bergeron–Findeisen mechanism. In order to grow to the size of a drizzle droplet, about 300 µm (0.1 inch) across, the cloud droplet must increase its volume more than 3,000 times and to attain the size of a raindrop 2 mm (0.08 inch) across it must grow almost 1 million times bigger. (The volume of a sphere is equal to $4/3\ \pi r^3$, where r is the radius.)

The Bergeron–Findeisen mechanism is a theory to explain how cloud droplets grow into raindrops in cold clouds (clouds in which the ambient temperature is below freezing). It is sometimes called the Wegener–Bergeron–Findeisen mechanism, because the German meteorologist Alfred Wegener suggested the first stage in the process in 1911. The Norwegian meteorologist Tor Bergeron was the first scientist to propose it in full in 1935 (*see* APPENDIX I: BIOGRAPHICAL ENTRIES for information about Wegener and Bergeron), and later the German meteorologist Walter Findeisen demonstrated it in large CLOUD CHAMBERS.

Cold clouds contain both ICE CRYSTALS and supercooled (*see* SUPERCOOLING) water droplets. The SATURATION VAPOR PRESSURE over an ice surface is lower than that over a liquid water surface. This is especially true at temperatures between about 5°F and -13°F (-15°C and -25°C), when the difference amounts to about 0.2 mb (20 Pa). Consequently, water will evaporate from the droplets and accumulate on the crystals by direct deposition from WATER VAPOR. The crystals grow, collide with one another, and stick together to form aggregations—SNOWFLAKES. This continues until the snowflakes are heavy enough to start falling. As they fall, the snowflakes collide with more supercooled droplets. The water freezes onto them, so the flakes keep on growing. Some are broken apart by air currents, and the splinters of ice produced in this way act as FREEZING NUCLEI for the formation of more ice crystals that join together into more snowflakes. Those snowflakes that remain intact fall from the base of the cloud. If the temperature in the air beneath the cloud is above freezing, the snowflakes will start to melt and some or all of them will reach the ground as rain. In middle latitudes, most rain SHOWERS consist of melted snow, even in the middle of summer.

A small region inside a cloud where ice crystals are growing more rapidly than they are elsewhere in the cloud at the expense of a concentration of supercooled droplets is called a precipitation-generating element. When they exceed a certain size, the ice crystals will fall through the cloud, generating precipitation by the Bergeron-Findeisen mechanism.

The alternative mechanism for raindrop formation is called collision theory. This theory that describes the way raindrops form in warm clouds, where no ice crystals are available and therefore the Bergeron-Findeisen mechanism does not apply. Warm clouds contain droplets of varying sizes. The larger ones fall through the cloud at a terminal velocity that varies with their size,



As it falls, the large droplet collides with the smaller droplets in its path. Only those small droplets that are close to the center of the path swept by the large droplet collide with it. Those farther away are carried to the sides by the airflow.

so large droplets fall faster than smaller ones. As they fall, the large droplets collide and coalesce with smaller droplets in their path. The rate at which collisions and coalescence occurs is measured by the collision efficiency and coalescence efficiency.

The collision efficiency is measured by the proportion of droplets in a cloud that collide with other droplets. Although it might seem that water droplets are crowded closely together inside a cloud, in fact they are widely separated in relation to their own size and so collisions are by no means inevitable. A large droplet has a higher terminal velocity than a small one and therefore falls faster. A warm cloud therefore consists of relatively large droplets falling through smaller ones. In order to collide, the small droplets must be very close to the center of the path followed by the large ones. If they are not, the displacement of air by the large droplets will sweep the small ones to the sides and away and collisions will not occur. Collision efficiency increases with the size of the large droplets. Droplets smaller than 20 μm in diameter are swept aside without colliding. Droplets more than about 40 μm across collide with most of the small droplets in their path. The higher the collision efficiency, the more rain the cloud will produce. Collision does not necessarily mean the droplets will coalesce.

Sweeping is a mechanism by which raindrops are believed to grow. It is a variant of the collision and coalescence theory that is based on the fact that the terminal velocity of a raindrop is proportional to its size. Large drops therefore fall faster than small drops. They will collide with some slower, smaller drops and these will merge with them (collision and coalescence). Other small droplets will be swept into the wake of the bigger drop and absorbed by them in that way.

Coalescence is the merging of two or more cloud droplets into a single, larger droplet. Colliding droplets may bounce away from each other. Droplets of similar size usually coalesce temporarily, oscillate, and then separate into two or more smaller droplets. But droplets of widely different sizes will coalesce to form a stable droplet.

The proportion of colliding cloud droplets that merge to form larger drops is known as the coalescence efficiency. Coalescence efficiency is greatest where there is the greatest difference in size between the large and small droplets. It also varies with the relative velocities of the droplets and the angle at which they collide. The higher the coalescence efficiency, the more rain the cloud will produce. Atmospheric electricity increases coalescence efficiency by placing opposite charges on the surfaces of droplets, so they are attracted to one another. The merging of cloud droplets that carry opposite electrostatic charges (*see* STATIC ELECTRICITY) on their surfaces is called electrostatic coalescence.

Falling raindrops engulf solid particles with which they collide, and the rain then carries the particles to the surface. This process is called washout. Particles are also removed from the air by FALLOUT, impaction (*see* AIR POLLUTION), and rainout (*see* CLOUD CONDENSATION NUCLEI).

rainfall regime A CLIMATE CLASSIFICATION that is based on rainfall frequency (*see* RAIN). It was devised by the British climatologist W. G. Kendrew and first published in his book *The Climates of the Continents.* Kendrew proposed six regimes.

(i) Equatorial regime. This comprises two seasons of heaviest rain, at or about the time the Sun is directly overhead, with drier periods between, but no dry season.
(ii) Tropical regime. There are two types of tropical regime. In the inner tropical, between the equator and latitudes 10°N and S, maximum rainfall occurs twice in the year, separated by a long dry season. In the outer tropical regime, between 10° and the TROPICS, the two wet seasons merge and the dry season is longer.
(iii) Monsoon regime. This has a marked summer maximum and a dry winter (*see* MONSOON). It occurs both inside and outside the Tropics.
(iv) Mediterranean regime. Most of the rain falls in winter, with either a single maximum in the middle of winter or two maxima, in spring and fall, and the summer is dry.
(v) Continental interior regime. This regime occurs in temperate latitudes. Most rain falls in summer. Winter rainfall is much less, but the winter is not completely dry.
(vi) West coastal regime. This regime occurs in temperate latitudes. Rain is abundant in all seasons, but heavier in the fall or winter than it is at other times.

Further Reading

Kendrew, W. G. *The Climates of the Continents.* Oxford: Oxford University Press, 1st ed. 1922, 5th ed., 1961.

rain forest A forest that grows where the rainfall is heavy and spread fairly evenly through the year. Rain forests grow in both the TROPICS and in temperate latitudes.

Tropical rain forest was first defined in 1898 by the German botanist and ecologist Andreas Franz Wilhelm Schimper (1856–1901), who also coined the term (in German, as *tropische Regenwald*). Schimper said the forest comprises evergreen trees that are at least 100 feet (30 m) tall, rich in thick-stemmed lianas (creepers), and with many woody and herbaceous (nonwoody) epiphytes growing on them. An epiphyte is a plant that grows on the surface of another plant, but that is not a parasite. This definition still stands. The forest trees form a continuous canopy. There are also trees up to 100 feet (60 m) tall that stand high above the canopy.

Temperate rain forest develops outside the Tropics, wherever the annual rainfall exceeds 60–120 inches (1,500–3,000 mm). It consists of broad-leaved evergreen trees, often with coniferous species, and with abundant climbers and epiphytes. This type of forest is found in coastal areas of the southeastern United States, northwestern North America, southern Chile, parts of Australia and New Zealand, and in southern China and Japan.

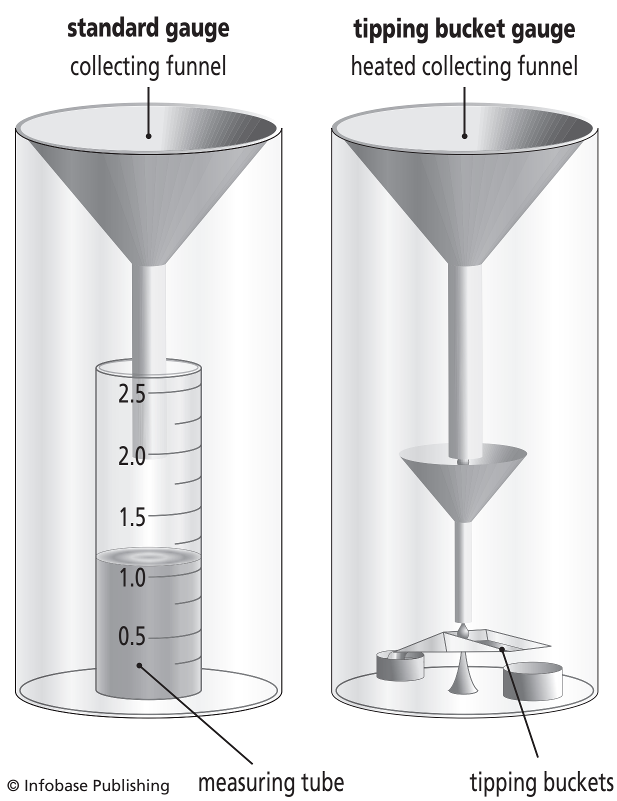
rain gauge The instrument that is used to measure the amount of rain that falls in a particular place during a given period of time, usually one day, is known as a rain gauge. The amount of rain that falls over a specified period into a particular rain gauge, or the amount that is estimated to have fallen during that period at a particular place, is known as the point rainfall. The point rainfall often refers to the amount of rain that fell during a single storm, or during a period of unusually wet or dry weather.

There are several ways to measure rainfall. The simplest is to leave an open-topped container exposed to the rain. This will collect rain, but water will also evaporate from it, especially after the rain has ceased falling, so it will not give an accurate reading. It is impossible to correct for this, because the rate of EVAPORATION varies with the air TEMPERATURE and wind speed.

The standard rain gauge is designed to minimize evaporation losses. It is called "standard" because it is the design that is approved internationally for use at WEATHER STATIONS. All standard rain gauges are made to the same specification and dimensions. When standard gauges are used, the scientists who use the data to prepare forecasts know that all the measurements reported to a meteorological center have been made in exactly the same way. If the staff at each station could decide for themselves how to make their measurements and what instruments to use, the data from one station would not be strictly comparable to that from another. What one station called 1.01 inches (25.65 mm) of rain, for example, another might call 1.00 inch (25.4 mm) and a third 1.02 inches (25.91 mm). The difference amounts to no more than a tiny one-hundredth of an inch (0.25 mm), but it would introduce an uncertainty into the data that is easily avoided by standardization.

The exterior of a standard gauge is a cylinder 7.9 inches (20 cm) in diameter that is mounted vertically with its top 39.4 inches (1 meter) above ground level. Rain falling into the cylinder enters a funnel that guides the water into a measuring tube inside the cylinder. The diameter of the measuring tube is 2.49 inches (6.32 cm), therefore the cross-sectional area of the measuring tube is one-tenth that of the mouth of the funnel. Consequently, a column of water 10 inches (or millimeters) high in the measuring tube represents one inch (or millimeter) of rain entering the funnel. Multiplying by 10 makes it easier to read the rainfall accurately. The measuring tube may be calibrated, or the height of water in it may be measured with a ruler or other measuring stick.

A standard gauge has to be visited at regular intervals, but it is also possible to measure and record rainfall automatically. The instrument most often used for this purpose is the tipping-bucket gauge.



The two types of rain gauge that are widely used at weather stations. The standard gauge (left) has to be visited at regular intervals to be read and reset. The tipping-bucket gauge (right) allows the rainfall to be recorded automatically.

Like the standard gauge, a tipping-bucket gauge is contained in a cylinder with a diameter of 7.9 inches (20 cm), but it has no measuring tube. Instead, rainwater entering the funnel is guided to a second, smaller funnel and from there into one of two buckets. Each bucket holds 0.01 inch (0.25 mm) of water. The two buckets are mounted on a rocker, like a seesaw. When 0.01 inch (0.25 mm) of water has flowed into a bucket, its weight tips the bucket downward. The bucket then makes an electrical contact that is transmitted to a recording pen which moves on a graph mounted on a rotating drum. At the same time, as the buckets tip the second bucket is positioned to collect water and the first bucket is emptied.

There are also gauges that automatically record the height of the water in the measuring tube. One design uses a float valve to do this and another measures the flow of an electric current through the water column, from which the height of the column is calculated.

A hyetograph is an instrument that measures and automatically records rainfall. It consists of a reservoir in which rainwater collects. The reservoir also contains a float that is connected mechanically to a pen. As the water accumulates the float rises, moving the pen, which traces a line on a chart fixed to a rotating drum.

Rainfall can also be measured automatically by a weighing gauge. In this device the collected water is fed into a cylinder that rests on a balance. Nowadays this is usually an electronic balance, but earlier instruments used a spring balance. The weight of the water is recorded on a graph.

All of these instruments are subject to errors. Although the standard gauge minimizes evaporation losses by enclosing the collecting funnel and measuring tube inside the outer cylinder, it cannot eliminate them entirely. Some water evaporates through the tube of the collecting funnel. The first rain to fall into the gauge wets the funnel and the film of water coating the funnel does not reach the measuring tube, bucket, or weighing cylinder. This is called wetting, and although the amount is no more than 0.04–0.08 inch (0.1–0.2 mm), this can be significant where rainfall is extremely light. Heavy rain can overflow tipping buckets, so they rock rapidly back and forth but under-record the amount of rainfall.

Wind causes even greater inaccuracies. EDDIES that form around the gauge carry a variable proportion of

RAINDROPS across the mouth of the funnel. Gauges are often placed inside a shield in order to minimize wind losses. The shield consists of a horizontal circular hoop, 20–40 inches (50–100 cm) in diameter, with baffles hanging vertically from it.

Trees, buildings, and other obstructions can shelter a rain gauge from rain that is falling obliquely. To avoid this, the distance between the gauge and the nearest obstruction should be at least equal to the height of the obstruction.

An optical rain gauge measures the intensity of rainfall. It transmits an infrared beam along a horizontal path 20–40 inches (50–100 cm) long to a detector. When the beam strikes a raindrop, the radiation is scattered forward. The detector records the SCATTERING, from which the number of raindrops per second and in a unit volume of air can be counted. This provides a continuous record of rainfall intensity, but it does not measure the amount of rain directly.

rainmaking Any attempt to induce PRECIPITATION to fall from a cloud that otherwise might not have released it can be called rainmaking. Several methods have been tried to achieve this. All them aim to induce the formation of CLOUD DROPLETS and then to stimulate their growth. This can be done by injecting suitable material into the cloud. The process is called CLOUD SEEDING.

raised beach A strip of land that contains rounded pebbles, sand, and seashells by which it can be recognized as having once been a beach, although it is now some distance above the sea shore. The location of the shore has changed because either the land has risen as a result of movements in the Earth's crust, such as GLACIOISOSTASY, or because the sea level has fallen. The accumulation of water in ICE SHEETS and GLACIERS is the most likely explanation for a fall in sea level (as opposed to a rise in land level).

Raoult's law A law that was formulated by the French physical chemist François-Marie Raoult (1830–1901) in 1886. It states that when one substance (the solute) is dissolved in another (the solvent), the partial pressure (*see* AIR PRESSURE) of the solvent vapor that is in equilibrium with the solution is directly proportional to the ratio of the number of solvent molecules to solute molecules.

The law means that the equilibrium vapor density (*see* BOUNDARY LAYER) above the surface of a solution is lower than that above the surface of pure solvent and the more concentrated the solution, the greater is the difference. Consequently, more water will enter the solution. CLOUD DROPLETS that form on hygroscopic nuclei (*see* CLOUD CONDENSATION NUCLEI) are solutions that are often quite concentrated. Raoult's law shows that such droplets will then grow rapidly by the CONDENSATION of more WATER VAPOR.

Rapid Climate Change (RAPID) A British program launched in 2001 and funded by the UK government through the Natural Environment Research Council that aims to quantify the likelihood and magnitude of rapid climate change in the future. The program cost £20 million (about $36 million) and runs from 2001 until 2007. It studies all aspects of rapid climate change, but concentrates especially on changes affecting the THERMOHALINE CIRCULATION in the Atlantic Ocean.

RAPID monitors change by means of moored devices called profilers. These are sensors that move vertically up and down wires connected to buoys on the sea surface and moorings on the seafloor. As they move, the sensors acquire data that they transmit to an orbiting satellite.

Further Reading

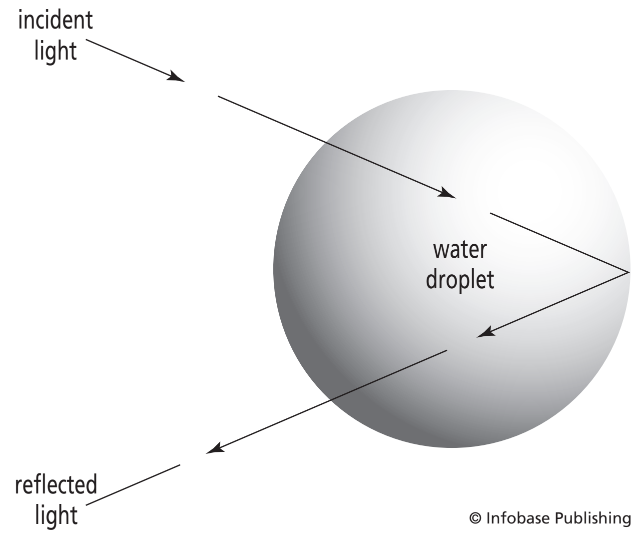
Natural Environment Research Council. "Welcome to the Rapid Climate Change Home Page." NERC. Available online. URL: www.noc.soton.ac.uk/rapid/rapid.php. Last modified January 19, 2006.

Rayleigh number A DIMENSIONLESS NUMBER, calculated by Lord Rayleigh (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), that describes the amount of TURBULENT FLOW in air that is being heated from below by CONVECTION. The Rayleigh number (*Ra*) is calculated from the equation:

$$Ra = [(g\Delta\theta)/k\upsilon\theta](\Delta z)^3$$

where g is the gravitational acceleration, $\Delta\theta$ is the POTENTIAL TEMPERATURE lapse in a layer of air with a depth Δz, k is the thermal conductivity of the air, and υ is the kinematic VISCOSITY of the air.

Convection will always produce turbulence when the amount of heating is too great for energy to be



In internal reflection, incident light rays pass through the water droplet to its far side from where they are reflected.

transferred by conduction between molecules and when the resulting air motion is too vigorous for LAMINAR FLOW to be sustained by viscosity. Turbulence will occur when the Rayleigh number exceeds approximately 50,000.

reflection The "bouncing" of light when it strikes an opaque surface. The angle at which light strikes a surface is known as the ANGLE OF INCIDENCE, and the angle at which it is reflected is the angle of reflection. The angle of reflection is always equal to the angle of incidence.

Objects that are not themselves sources of light are made visible by the light reflected from them. If the surface is smooth, then all the light will strike it and be reflected from it at the same angle. If the surface is uneven, the angle at which light strikes it will vary from place to place, as will the angle at which it is reflected. Such uneven reflection scatters the light, producing multiple or distorted images.

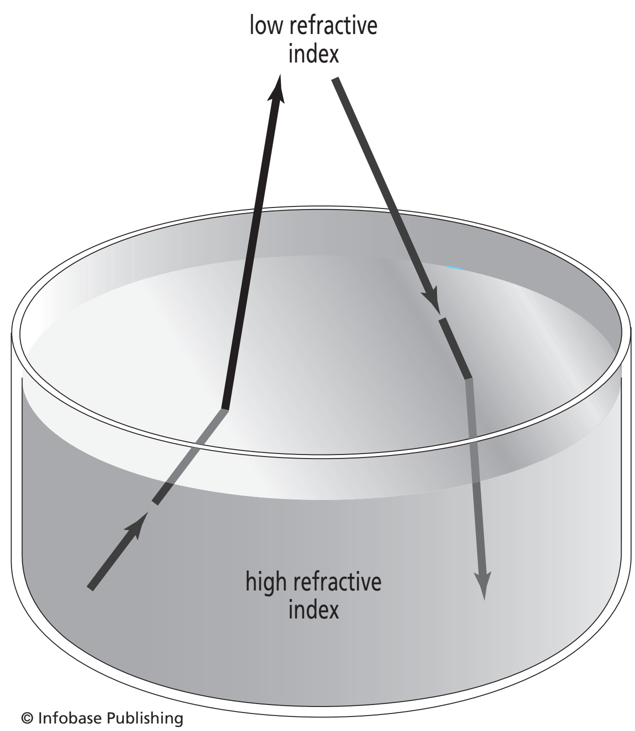
Light that has passed through a transparent body may be reflected from the inside surface of the body on the far side. This is called internal reflection. The internal reflection from water droplets is partly responsible for such OPTICAL PHENOMENA as rainbows.

refraction When light passes obliquely from one transparent medium to another transparent medium through which it travels at a different speed, the light is bent, or refracted. The extent of the refraction is proportional to the difference in the speed of light in the two media and to the angle at which the light enters.

The ratio of the speed of light in air to the speed of light in the medium is a constant for that medium, known as its refractive index. Air has a refractive index of 1.0003, the refractive index of ice is 1.31, that of water is 1.33, and that of window glass is 1.5.

The angle through which light is refracted is known as the angle of refraction. This angle varies according to the angle at which the light strikes the boundary between the two media and also to the difference in their refractive indices. The smaller the incident angle, the greater will be the angle of refraction, and when the incident angle is 90°, light is not refracted at all, although its speed changes. The greater the difference in the refractive indices of the two media, the greater will be the angle of refraction.

When light passes from a medium with a low refractive index into one with a high refractive index, it is bent toward the vertical in relation to the surface



Light rays bend as they pass across the boundary between two transparent substances, such as air and water, through which light travels at different speeds.

between the two media. Light passing from a high to a low refractive index is bent in the opposite direction, away from a line vertical to the boundary.

remote sensing Remote sensing is the acquisition of information about an object without being in direct physical contact with that object. Instruments carried by a WEATHER BALLOON are in contact with the air they are monitoring, so although the meteorologists who receive data from them are not in contact with that air, the sensors are, so the sensing itself is direct, not remote. An orbiting satellite, in contrast, transmits atmospheric data that it acquires from outside the atmosphere. This sensing is remote and works by acquiring images in various parts of the electromagnetic spectrum, such as the microwave, infrared, visible light, and ultraviolet wavebands. Scientists on the ground are able to interpret these images to obtain information about various aspects of climate, such as TEMPERATURES, clouds, and HUMIDITY.

A photopolarimeter–radiometer (PPR) is an instrument used in remote sensing. It supplies data from which the temperature and cloud formation in the atmosphere of a planet or satellite can be determined, as well as some surface detail. The PPR measures the intensity and polarization of sunlight in the visible part of the SOLAR SPECTRUM.

residence time The atmosphere is a dynamic system. DUST particles, mineral grains, POLLEN, SPORES, as well as molecules of WATER VAPOR and the other gases that constitute the air are constantly entering the atmosphere and leaving it. The residence time of any individual atom, molecule, or particle is the length of time that it remains in the air.

Residence time (R) is calculated as the total mass (M) of the substance divided by the FLUX (F), which is the rate at which it is entering and leaving the air ($R = M/F$). The larger the total mass the longer the residence time will be. NITROGEN is the principal atmospheric gas. Although a very large amount of nitrogen leaves the air every day due to nitrogen fixation and enters it by denitrification, the atmosphere contains approximately 4,466 million million tons (4.466×10^{15}, or 4.06×10^{18} kg). The flux therefore represents only a minute fraction of the total mass of nitrogen in the air. Consequently, the average time a nitrogen molecule spends in the air between being released by denitrification—the bacterial process that releases gaseous nitrogen from the breakdown of nitrogen compounds—and removed again by nitrogen fixation is about 42 million years.

The atmosphere contains about 1,200 million million tons (1.2×10^{15}, or 1.09×10^{18} kg) of OXYGEN. Oxygen is removed from the air mainly by respiration and is returned to it by the process of PHOTOSYNTHESIS. An oxygen molecule remains in the air for an average of about 1,000 years.

CARBON DIOXIDE is present in trace amounts and is cycled rapidly by photosynthesis and RESPIRATION. A CO_2 molecule remains airborne for an average of about 55 years. METHANE has a residence time of about 11 years. Methyl chloride (CH_3Cl), which is produced by chemical reactions in seawater and is the largest natural source of atmospheric chlorine, has a residence time of 1.5 years. Halons (*see* OZONE LAYER) have residence times of 20 years for H-1211 (CF_2ClBr) and 65 years for H-1301 (CF_3Br). CFC-11 and CFC-12, which are the commonest CFCs, have residence times of 50 years and 100 years respectively.

There is even more WATER on the Earth than there is nitrogen. The total amount of water is about 1.54×10^{18} tons ($1,400 \times 10^{18}$ kg). The residence time of a water molecule is shorter than that of a nitrogen molecule, however, because the flux is much greater. Much more water is moving through the HYDROLOGICAL CYCLE than there is nitrogen moving through the nitrogen cycle. A water molecule spends an average 4,000 years in the ocean, about 400 years in lakes, rivers, GROUNDWATER, and as ice, and only about 10 days in the atmosphere.

Solid particles remain in the air for quite short periods. They obey the same law as gas molecules, but their total mass is much smaller than that of the atmospheric gases and their flux rate is greater. Some particles act as CLOUD CONDENSATION NUCLEI and are removed by rainout or snowout (*see* SNOW). Others are swept from clouds and from the air beneath clouds by PRECIPITATION and so are removed from the air by washout. Washout is much more efficient than rainout at removing particles. In addition, solid particles settle by gravity and the rate at which they do so must also be taken into account. Most particles bigger than 0.00004 inch (1 μm) in diameter are removed from the air by settling, and those more than 0.0004 inch (10 μm) usually remain in the air for only a few minutes. Smoke particles usually remain airborne for a few hours.

Residence times

Substance	Symbol	Atmospheric residence time
nitrogen	N_2	42 million years
oxygen	O_2	1,000 years
CFC-114	$C_2F_4Cl_2$	300 years
HCFC-23	CHF_3	250 years
CFC-12	CF_2Cl_3	100 years
CFC-113	$C_2F_3Cl_3$	85 years
H-1301	CF_3Br	65 years
carbon dioxide	CO_2	55 years
CFC-11	$CFCl_3$ 5	50 years
carbon tetrachloride	CCl_4	42 years
H-1211	CF_2ClBr	20 years
HCFC-22	CHF_2Cl	13.3 years
methane	CH_4	11 years
HCFC-124	C_2HF_4	5.9 years
methyl choride	CH_3CL	1.5 years
HCFC-123	$C_2HF_3Cl_2$	1.4 years
water	H_2O	10 days
ammonia	NH_3	7 days
smoke		hours
large particles		minutes

The table above lists the atmospheric residence times of a range of substances.

respiration Respiration is the process by which living organisms release energy by the oxidation of carbon. Breathing is the pumping action by which vertebrate land animals draw air into their lungs to obtain OXYGEN and expel CARBON DIOXIDE.

Oxidation was once thought to be a chemical reaction in which a substance acquires oxygen. The reverse process, in which a substance loses oxygen, and also a reaction in which a substance acquires hydrogen, was known as reduction. Nowadays these terms are defined more generally. Oxidation is a reaction in involving a loss of electrons and reduction is a reaction involving the acquisition of electrons. Consequently, it is possible for an oxidation reaction to take place in the absence of oxygen.

The carbon oxidized in respiration is in the form of glucose ($C_6H_{12}O_6$), a sugar that is produced in green plants and some BACTERIA and cyanobacteria by the process of PHOTOSYNTHESIS. In Archaea, some bacteria, and some fungi respiration is anaerobic (takes place in the absence of oxygen). The anaerobic reaction in the case of yeast, which is a fungus, is known as fermentation and it can be summarized as:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

C_2H_5OH is ethanol, which is also called ethyl alcohol or just alcohol.

Aerobic respiration, which requires the presence of oxygen, can be summarized as:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Plants and all animals practice aerobic respiration. Species that dwell on land obtain their oxygen directly from the atmosphere. Aquatic organisms rely on oxygen that is dissolved in the water (they do not obtain oxygen by splitting water molecules).

In fact, the reaction in both cases takes place as a sequence of steps and is a great deal more complicated than this summary makes it appear. The energy that is released is used to attach a phosphate group to adenosine diphosphate (ADP), making it into adenosine triphosphate (ATP). ATP is transported through the organism, and wherever energy is required a phosphate group is discarded (ATP becomes ADP) with a release of energy. All the energy used by living organisms from bacteria to trees to people is transported and released by the ADP $\leftrightarrow$ ATP reaction.

So far as the atmosphere is concerned, the process of respiration returns to the air the CO_2 that is removed by photosynthesis and aerobic respiration removes from the air the oxygen that is released by photosynthesis. Between them, photosynthesis and respiration maintain a constant atmospheric concentration of these two gases.

response time The time that elapses between a change in the amount of energy that is available in one part of the climate system and the effect that energy produces. This varies greatly according to the type of surface.

For example, in early spring there is an increase in the amount of solar heat that reaches the ground. If snow and ice cover the ground, however, most of that heat is reflected. This greatly reduces the warming effect of the spring sunshine and the extent to which it warms the air in contact with the surface. The climate responds slowly to the increase in energy. Where the ground is free from ice and snow, it warms rapidly and the response time of the climate is short.

The oceans absorb a large amount of heat before the water TEMPERATURE increases. This is because of the high HEAT CAPACITY of water. Air in contact with the sea surface warms eventually, but the absorption of heat delays that response. Ocean currents also transport the warmed water over long distances, and it may also be carried deep below the surface and held there for years before returning to the surface and warming the air. In this case the response time is very long.

return period The frequency with which a rare natural phenomenon may be expected to occur. It is based on recorded occurrences in the past and is then expressed as a range of values. These values also represent the statistical probability that the phenomenon will occur in any particular year. For example, records and calculations may indicate that a certain area is liable to be flooded once every 10 years. There is therefore a 10 percent chance that it will be flooded in any particular year, and the flood that affects it is known as a 10-year flood. Ten years is then said to be the return period for that event. Using the same method, there can be 50-year, 100-year, or 1,000-year floods.

The less frequent the event, the more severe it is when it happens. In 1952, the English village of Lynmouth was severely damaged by flooding. This was an event so unlikely that it was classed as a 50,000-year flood. Wind storms, BLIZZARDS, DROUGHTS, and other types of hazardous weather can be assigned probabilities in the same way.

Further Reading

Allaby, Michael. *Floods*. Rev. ed. Dangerous Weather. New York: Facts On File, 2003.

Reynolds number (*Re*) A DIMENSIONLESS NUMBER that is used to measure the extent to which a fluid flows smoothly (*see* LAMINAR FLOW) or turbulently (*see* TURBULENT FLOW). For a fluid flowing through a pipe it is calculated by:

$$Re = v\rho l/\eta$$

where v is the flow VELOCITY, p is the DENSITY of the fluid, l is the radius of the pipe, and η is the VISCOSITY of the fluid. For air, Re can be calculated by

$$Re = LV/v$$

where L is the distance over which the air is moving, V is its velocity, and v is its kinematic viscosity, which is equal to approximately 16×10^{-5} ft²/s (1.5×10^{-5} m²/s). If Re is less than about 1,000, the flow is dominated by viscosity. If Re is greater than about 1,000, the flow is dominated by turbulence.

Except on a very small scale, such as the flow around a spherical ball, Re is usually much larger than 10^3. Typically it is 10^6 or 10^7.

The number was discovered by the physicist Osborne Reynolds (*see* APPENDIX I: BIOGRAPHICAL ENTRIES).

Rhyacian A period during the PALEOPROTEROZOIC era of the Earth's history that began 2,300 million years ago and ended 2,050 million years ago. At this time the continents were smaller than those existing today, but they moved faster (*see* PLATE TECTONICS) because the magma beneath the Earth's crust was hotter and less viscous than it is now. (*See* APPENDIX V: GEOLOGIC TIMESCALE.)

ridge A long, tonguelike protrusion of high AIR PRESSURE into an area of lower pressure. The waves in the polar front JET STREAM associated with the index cycle (*see* ZONAL INDEX) that extend toward the North Pole are also called ridges.

A ridge in which the isobars (*see* ISO-) make a V-shaped point is called a wedge.

root-mean-square (RMS) Calculating the RMS is a technique for determining the value of a quantity that is fluctuating. RMS is calculated by sampling the values, squaring them, averaging them, and then calculating the square root of the mean.

Rossby number (*Ro*) A DIMENSIONLESS NUMBER that was discovered by the Swedish-American meteorologist Carl-Gustav Rossby (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). The Rossby number is the ratio of the ACCELERATION of moving air due to the PRESSURE GRADIENT and the CORIOLIS EFFECT: Ro = (relative acceleration)/(Coriolis effect). It is given by:

$$Ro = U/\Omega L$$

where U is the horizontal wind VELOCITY, Ω is the angular velocity of the Earth, and L is the horizontal distance over which the wind travels.

Rossby waves (long waves, planetary waves) Waves that develop in moving air in the middle and upper troposphere. They have wavelengths (*see* WAVE CHARACTERISTICS) of 2,485–3,728 miles (4,000–6,000 km) and are named after Carl-Gustav Rossby (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), the Swedish-American meteorologist who discovered them.

The angular wave number, also called the hemispheric wave number, is the circumference of the Earth measured at a specified latitude divided by the wavelength of the Rossby waves associated with a particular weather pattern. It gives the number of waves of that wavelength that are required to encircle the Earth and, therefore, the number of times the weather pattern repeats around the world.

The irregular change that takes place in the Rossby waves surrounding each hemisphere as their amplitude oscillates between a maximum and a minimum is called vacillation. The series of steps by which the oscillation occurs makes up the index cycle (*see* ZONAL INDEX).

runoff Runoff is the movement of water that falls to the ground as PRECIPITATION, including melting SNOW, FROST, DEW, and FOG droplets, and that then flows across the ground surface directly into rivers or lakes. As it crosses the ground, some of the water filters into the soil, eventually joining the GROUNDWATER. The remainder, or net runoff (symbolized by Δr), is not available to plants. Measurement of the amount of runoff is used in calculating the WATER BALANCE for an area.

S

Saffir/Simpson hurricane scale For more than a century, wind force was reported using the scale that had been devised by Admiral Beaufort (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). The BEAUFORT WIND SCALE is still in use, but it has one major disadvantage: It is designed for temperate regions, where winds stronger than 75 MPH (120.6 km/h) are very uncommon. All such winds are classed on the Beaufort scale as being of hurricane force.

This is inadequate for those parts of the world that experience real TROPICAL CYCLONES. All of these cyclones produce winds of greater force than the 75 MPH, force 12, which is the highest value on the Beaufort scale, but they vary considerably in the winds they generate and, therefore, in the damage they are capable of inflicting.

To address this difficulty, meteorologists at the U.S. Weather Bureau (now part of the NATIONAL WEATHER SERVICE) introduced in 1955 an extension to the Beaufort scale: the Saffir/Simpson hurricane scale, named after the scientists who devised it. It adds five more points to the wind scale, but it also conveys more information than does the Beaufort scale. As well as wind speed and a general description of the type of possible wind damage, it includes the surface AIR PRESSURE at the center of the storm and the height of the STORM SURGE. The pressure indicates the intensity of the storm—the lower the pressure the more violent the storm will be—and information about the anticipated storm surge is vital, because tropical cyclones begin at sea and affect mainly coastal areas. Tropical cyclones everywhere are now classified according to the Saffir/Simpson scale, and their values are determined by their core pressure and not by the wind speeds they sustain.

Sahel Sahel is the name of the region in northern Africa that lies along the southern margin of the Sahara. The region extends from Senegal in the west to Sudan and Ethiopia in the east and includes parts of Senegal, Guinea Bissau, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, Central African Republic, Sudan, Eritrea, and Ethiopia.

The Sahel forms a transitional zone between the desert to the north and the humid tropical grasslands to the south. The vegetation comprises short grasses, tall herbs, and thorn scrub with species such as acacias (*Acacia* species) and baobab trees (*Adansonia digitata*), but the plants are scattered and there are few places where the vegetation cover is continuous.

The climate is semi-arid and strongly seasonal, with a short rainy season in summer. Niamey, Niger, receives an average 22 inches (554 mm) of rain a year, but no rain at all falls between the end of October and the beginning of March. Most of the rain, about 20 inches (495 mm), falls in June, July, August, and September. N'Djamena, the capital of Chad, receives no rain from the end of October until the beginning of April, and of the 29 inches (744 mm) it receives in an average year, 24 inches (610 mm) fall in July, August, and September. August is the wettest month.

Temperatures change little through the year, and the climate is hot. April is the warmest month at

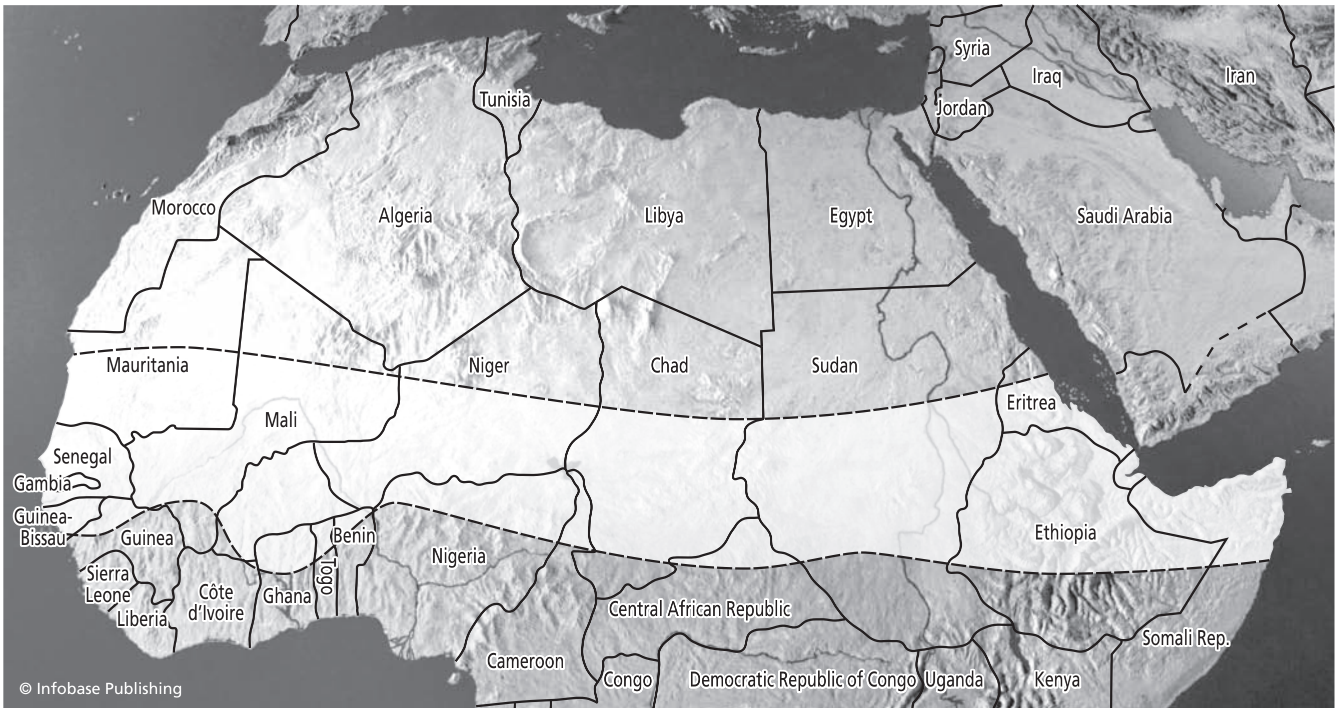
Saffir/Simpson Hurricane Scale

Category	Pressure at center	Wind speed	Storm surge	
	mb in. of mercury cm. of mercury	mph km h^{-1}	feet meters	Damage
1	980 28.94 73.5	74–95 119–153	4–5 1.2–1.5	Trees and shrubs lose leaves and twigs. Mobile homes destroyed.
2	965–979 28.5–28.91 72.39–73.43	96–110 154.4–177	6–8 1.8–2.4	Small trees blown down. Exposed mobile homes severely damaged. Chimneys and tiles blown from roofs.
3	945–964 27.91–28.47 70.9–72.31	111–130 178.5–209	9–12 2.7–3.6	Leaves stripped from trees. Large trees blown down. Mobile homes demolished Small buildings damaged structurally.
4	920–944 27.17–27.88 69.01–70.82	131–155 210.8–249.4	13–18 3.9–5.4	Extensive damage to windows, roofs, and doors. Mobile homes destroyed completely. Flooding to 6 miles (10 km) inland. Severe damage to lower parts of buildings near exposed coasts.
5	920 or lower below 17.17 below 69	more than 155 more than 250	more than 18 more than 5.4	Catastrophic. All buildings damaged, small buildings destroyed. Major damage to lower parts of buildings less than 15 ft (4.6 m) above sea level to 0.3 mile (0.5 km) inland.

N'Djamena, when the average daytime temperature is 107°F (42°C) and has been known to reach 114°F (46°C). In December, the coldest month, the average daytime temperature is 92°F (33°C) and 101°F (38°C) has been recorded. It is much cooler at night, but the lowest nighttime temperature recorded is 47°F (8°C), and the average temperature at night in December and January is 57°F (14°C). Niamey experiences almost identical temperatures.

Averages can be misleading, however. It is the northward movement of the INTERTROPICAL CONVERGENCE ZONE (ITCZ) that brings the tropical rain belt to the Sahel and causes the summer rains, but occasionally the ITCZ remains to the south. When this happens, the rains are lighter than usual or, if the ITCZ remains a long way to the south, they fail altogether. During the late 1960s, the Sahel experienced a sequence of years when the summer rains were light. This produced DROUGHT. Then, in 1972 and 1973, the rains failed completely, and the rainfall did not return to normal until the 1980s.

It was not the first time the Sahel had been afflicted with severe drought. Several droughts occurred in the 17th century and caused serious famines. Those droughts were associated with the coldest part of the LITTLE ICE AGE. No one knows what caused the



The Sahel forms a belt along the southern margin of the Sahara, extending from Senegal to Sudan, Eritrea, and Ethiopia.

drought in the 20th century, although it did coincide with the latter part of a period when temperatures were falling sharply throughout the Northern Hemisphere.

Some of the people of the Sahel grow crops around the oases. Others live a seminomadic life, taking their herds and flocks of cattle, sheep, goats, and camels to traditional seasonal pastures. The drought that peaked in the 1970s proved devastating. It is estimated that between 100,000 and 200,000 people and up to 4 million cattle died. Countless more people were forced to migrate south across the national frontiers that are a legacy of European colonialism. It was the Sahel drought that alerted the international community to the difficulties facing people who live along the borders of deserts.

It is sometimes asserted that overgrazing caused the drought, but this is untrue. It was an entirely natural event and was not the fault of the people living in the region. Overgrazing did exacerbate its effects, however. As the pastures failed, livestock was crowded into increasingly smaller areas, where they did destroy the sparse vegetation. Governments also encouraged nomadic people to settle in permanent villages. This gave them access to medical care and schools, but it also placed excessive pressure on the grazing around the villages.

Further Reading

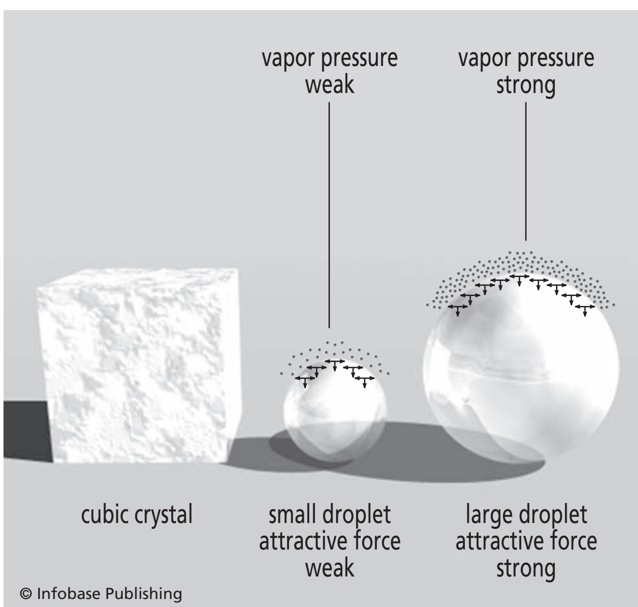
Allaby, Michael. *Droughts*. Rev. ed. Dangerous Weather. New York: Facts On File, 2003.

salt crystal The solid form that common salt (sodium chloride, NaCl) takes when it comes out of solution. The basic crystal is cubic in shape, about 0.0004 inch (10 μm) along each side, and it grows by the addition of more cubes.

Salt enters the air when drops of sea spray evaporate. The tiny crystals are then carried by air currents. Salt is hygroscopic, which means it dissolves in water that its crystals absorb from the atmosphere and airborne salt crystals act as hygroscopic nuclei. These are the most efficient of all CLOUD CONDENSATION NUCLEI. Water will condense onto a salt crystal at a relative HUMIDITY as low as 75 percent. Salt crystals are sometimes used in CLOUD SEEDING, where their effect is to increase the range of size of CLOUD DROPLETS. This increases the likelihood of PRECIPITATION, because some of the droplets grow large enough to fall and continue growing by collision and coalescence (*see* RAINDROPS) as they do so.

The efficiency of using salt crystals for cloud seeding is initially due to the readiness with which they dissolve in water. When a crystal dissolves, the resulting droplet is a fairly strong saline solution. The vapor pressure (*see* WATER VAPOR) is always lower over a solution than it is over pure water, so water evaporates more slowly from the solution. Once they form, therefore, saline cloud droplets resist EVAPORATION. More water condenses onto them, and as the droplets grow, the salt solution is diluted. This increases the vapor pressure.

The accumulation of more water would also increase the rate of evaporation if it were not for a counteracting effect that is due to the size of a droplet. Water molecules are linked by weak hydrogen bonds (*see* CHEMICAL BONDS). Molecules are held less firmly at the surface than they are in other parts of the body of liquid, because above the surface there are no molecules to which they can be linked. The attraction between molecules at the surface is strongest if the surface is flat. It is weaker over a curved surface by an amount that is proportional to the degree of curvature. Consequently, small droplets evaporate faster than large droplets.



Salt crystallizes into very small cubes that dissolve to form tiny droplets of salt water. The vapor pressure over the solution is weak, reducing the rate of evaporation. As the droplets grow, the solution becomes more dilute and the vapor pressure increases, tending to increase the rate of evaporation. At the same time, however, their surface curvature decreases. This increases the intermolecular forces at the surface and reduces the rate of evaporation.

As the saline droplet begins to grow and the vapor pressure over it increases, it also grows larger and its surface becomes less curved. This reduces the rate of evaporation from it.

The overall result is that salt crystals readily cause water vapor to condense, and the resulting droplets tend to survive long enough to grow. They continue to grow until they attain a size that is in equilibrium with the amount of moisture present in the cloud.

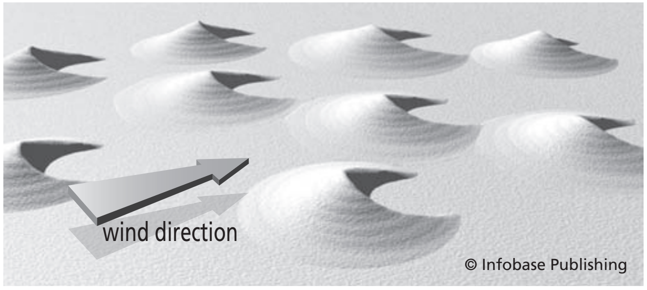
sand Sand is a granular material that results from the WEATHERING of rock. To a geologist, sand is defined only by the size of its grains. There are several classifications of particle size. In the Udden–Wentworth scale, which is widely used by geologists, sand grains are 0.0025–0.079 inch (0.0625–2.0 mm) across. Soil scientists use a different scale, with sand comprising grains 0.02–0.079 inch (0.5–2.0 mm) in the U.S. scale and 0.0008–0.079 inch (0.02–2.0 mm) in the international scale.

Composition is much less important, and sand can be made from the crushed remains of seashells, skeletons, fragments of volcanic rock, or almost any mineral. Most beach sand contains calcium carbonate ($CaCO_3$) fragments from seashells. In fact, though, most sand is made from silicate minerals, of which quartz (silica, or silicon dioxide, SiO_2) is by far the most common. Desert sand consists almost entirely of quartz.

Sand grains that have been lifted from the ground by wind and are transported through the air are known as blowing sand. A wind of 12 MPH (20 km/h) will raise sand grains smaller than 0.01 inch (0.25 mm) in diameter provided they are dry. Strong local convergence (*see* STREAMLINE) over a sandy desert will produce WHIRLWINDS, and a strong wind blowing over a wider area will produce a SANDSTORM. *See also* AQUIFER.

sand dune Dry sand is easily transported by wind, and it accumulates in particular places, where the wind may pile it into large heaps, called sand dunes. As well as building sand dunes, the wind also shapes them.

If there is abundant sand, a wind that blows almost always from a single direction will build transverse dunes. These are long, with the gradual slope on



A barchan dune is crescent-shaped and formed by wind that blows predominantly from a single direction.

the side facing the wind, and the line of the dunes is at right angles to the wind direction. Transverse dunes can be up to 60 miles (96 km) long and up to 300 feet (90 m) high, and they move downwind at up to about 80 feet (25 m) a year.

Transverse dunes sometimes develop wavy crests, so the face of the dune faces alternately into and away from the wind direction. Dunes of this type are called aklé dunes.

If the wind direction varies to either side of an average direction, it will build longitudinal dunes. These are aligned with the average wind direction. Longitudinal dunes have long, sharp, sinuous crests. In some places, especially in the western Sahara, the biggest of them are known as seif dunes, which can stretch for hundreds of miles. Their curved shapes resemble sword blades, and seif is from *sayf,* the Arabic word for sword.

Where the supply of sand is limited, winds blowing from either side of an average direction will blow the sand into a crescent shape, with the horns pointing downwind. If the crescent is narrow, so the horns are close together, this is called a parabolic dune—the shape is that of a parabola. If the horns are fairly wide apart, so the crescent is open, it is a barchan dune. Barchans are up to about 100 feet (30 m) high, and the tips of their horns are up to 1,200 feet (370 m) apart. Where there is enough sand, adjacent barchans may join to form an aklé dune, and sometimes one limb of a barchan can be blown away altogether, leaving the remaining limb as an isolated seif dune.

If there is no predominant wind direction, the sand may form star dunes, also called stellar dunes. A star dune consists of a series of ridges that radiate from a central point, making a shape resembling a star. Dunes of this shape can also form where other dunes intersect. A dune of this, intersecting, type is called a rhourd.

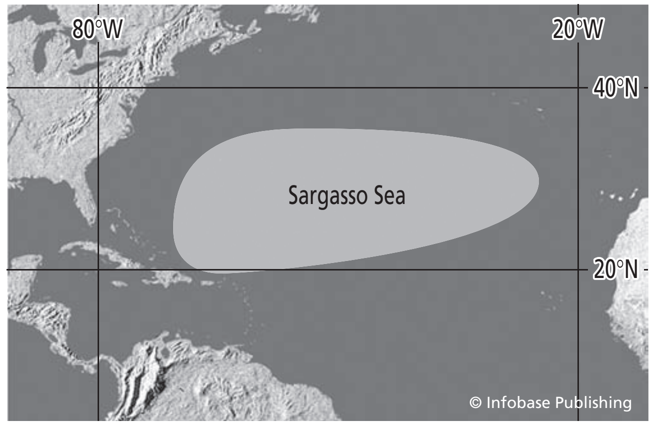
The largest sand formation of all is called a draa. A draa is a ridge or chain of sand dunes, sometimes more than 1,000 feet (300 m) high, and 0.3–3 miles (0.5–5 km) from its nearest neighbor. Draas are found in the sand seas, or ergs, of the Sahara. Intersecting draas form rhourds.

Sand dunes form from sand grains that are blown up the shallow windward slope and fall from its crest down the steeper slope, which is at an angle of about 32°. The constant movement of sand from one side of the dune to the other causes the dune to move in the direction of the wind. Draas move 0.8–2 inches (2–5 cm) a year. Barchan dunes move an average 30–65 feet (10–20 m) a year.

Seif dunes are long, tapering, and slightly curved.

A star dune consists of ridges that radiate from a central point. The arrows indicate the direction of the winds that formed the dune.

A sandstorm approaching a town in Kansas, from "Effect of Dust Storms on Health," U.S. Public Health Service, Reprint No. 1707 from *Public Health Reports,* 50, No. 40, October 4, 1935 *(Historic NWS Collection/NOAA)*



The roughly elliptical Sargasso Sea lies in the western North Atlantic and is enclosed by ocean currents that flow clockwise around it.

sandstorm A wind storm becomes a SAND storm if the wind lifts sand grains into the air and transports them. Sandstorms often travel long distances. The threshold velocity (*see* WIND SPEED) for dry, medium-sized sand grains about 0.01 inch (0.25 mm) in diameter is 12 MPH (19 km/h). Winds of more than 15 MPH (24 km/h) will raise enough sand to cause a sandstorm provided the air is unstable (*see* STABILITY OF AIR).

Wherever there is loose, dry sand, a wind of this speed will raise sand high enough to greatly reduce visibility and drive it with enough force to make exposure to it extremely uncomfortable. The wind blows horizontally, however, and although collisions between sand grains and the turbulence of the air (*see* TURBULENT FLOW) can raise the sand a short distance above the ground, it cannot lift it high enough for it to travel far. In unstable air, however, upcurrents can lift the sand to a considerable height. A sandstorm is produced in the same way as a dust storm, from which it differs only in the size of particles involved.

Sargasso Sea An area in the western North Atlantic Ocean that lies approximately between latitudes 20°N and 35°N and longitudes 30°W and 70°W. The sea is roughly elliptical in shape and occurs inside a system of ocean currents that rotate clockwise. The Gulf Stream, Canary Current, and North Atlantic Drift flow around its edges (*see* APPENDIX VI: OCEAN CURRENTS).

The waters of the Sargasso Sea are relatively calm. Winds are light, the EVAPORATION rate is high, and rainfall is low. The water is very clear and warm, with an average temperature of 64°F (18°C). The high rate of evaporation combined with low PRECIPITATION produce water with a salinity of 36.5–37.0 per mil. The average salinity of seawater is about 35.0 per mil. The sea is famous for its abundance of gulf weed, a brown, floating seaweed (several *Sargassum* species). It is not true that ships have ever been caught and trapped by the weed.

The Sargasso Sea is the breeding ground of the American and European eels (*Anguilla rostrata* and *A. anguilla* respectively). The larvae of European eels drift with the Gulf Stream, taking about three years to reach the cool, shallow waters off the coast of Europe, where they turn into elvers and migrate into rivers. American eels breed in the western part of the Sargasso Sea, and their larvae take only one or two years to reach the mouths of rivers.

satellite instruments Orbiting satellites are able to acquire data that is inaccessible to observers on the ground. Satellites have a wide field of view. Those in geostationary ORBITS monitor the surface from the equator almost to the pole, while satellites in polar or Sun-synchronous orbits scan the entire surface of the Earth every day. Their field of view allows satellites to produce mesoscale images, which are images that extend horizontally from 0.6–60 miles (1–100 km). METEOROLOGY at this scale, called mesometeorology, became feasible once satellite images showed the clouds associated with entire weather systems.

Having acquired data, satellites transmit them to a surface center, often by a method known as automatic picture transmission (APT). Usually, APT images have a resolution of 2.5 miles (4 km) and are transmitted at two lines per second. Images are transmitted as soon as they have been taken, rather than having to be stored for transmission later, as was the case with earlier equipment.

The images themselves are in digital form. A digital image is a picture compiled from a continuously varying stream of data received from an orbiting satellite or other remote source. The continuous variation is converted into discrete variation, in which the data change in small steps. Each discrete change is then given a numerical value as a picture element (conventionally abbreviated to "pixel") and assigned a location defined by coordinates.

High-resolution picture transmission (HRPT) is a method used to transmit images with a resolution of 0.7 mile (1.1 km), allowing them to depict features 0.5 mile (0.8 km) across. HRPT transmits two visible and three infrared channels.

False colors are used in many satellite images. These are colors that differ from the actual colors of the surfaces they represent. Instruments carried on satellites are able to detect radiation at any wavelength (*see* WAVE CHARACTERISTICS), including wavelengths outside the waveband to which the human eye is sensitive. The different wavelengths all convey useful information and the allocation of fairly arbitrary colors to them makes the areas emitting them clearly visible. In many false-color images infrared radiation appears as visible red. Vegetation is highly reflective to infrared wavelengths, and so it often appears red in false color pictures.

The use of satellite images to identify areas of the Earth that are experiencing deforestation, DROUGHT, or desert encroachment is known as vegetation index mapping. The greenness of plant cover can be measured from images transmitted by satellites in polar orbit and the health of vegetation inferred by comparing the color to a series that have been compiled into an index.

The operational linescan system (OLS) is the primary imaging system used on some of the satellites in the DEFENSE METEOROLOGICAL SATELLITE PROGRAM. Because the background to the images is dark, it is possible to increase the gain on the OLS photomultiplier tube at night. This allows the OLS to detect LIGHTNING discharges, and the system has produced the longest set of data for lightning, dating from 1973. It also detects waste gas flares at oil wells and has revealed the large extent of this practice. The OLS scans the whole Earth once every day at visible and infrared wavelengths with a resolution of 1.74 and 0.37 miles (2.8 and 0.6 km).

Microwave images of SNOW- and ICE-covered areas that are received from satellites are allotted colors according to a code based on a unit called the brightness temperature. Brightness temperatures correspond closely to the intensity of the microwave radiation, but they are given values in kelvins (*see* UNITS OF MEASUREMENT) to reflect differences in EMISSIVITIES from different surfaces. At a microwave wavelength of 1.55 cm, for example, ice has a brightness temperature of 190K or more, but water has a lower brightness temperature, of less than 160K. The boundary between water and SEA ICE shows clearly on the resulting color-coded image. Brightness temperatures vary with the wavelength of the microwave radiation, and by comparing brightness temperatures at two different wavelengths it is possible to calculate the depth of the snow covering an area.

A particular problem occurs with satellite images near to coasts. It is called land contamination, and it is the effect of the footprint, about 30 miles (50 km) in diameter, which occurs near coasts in satellite images. Land contamination occurs because some of the radiation received at the satellite comes from land and some from the ocean, making the data imprecise near coasts. This is especially important where the land is covered with ice, but the sea is not, because it can make it appear that ice covers coastal waters.

Satellites monitoring the Earth's atmosphere and surface carry a variety of instruments to capture the data they transmit to the ground. Some of these are briefly described here.

A radiometer measures electromagnetic radiation. It may be passive or active. A PASSIVE INSTRUMENT measures the radiation falling upon it. An ACTIVE INSTRUMENT emits a signal that is reflected back to it and compares the emission with its reflection. A radiometer may be designed to respond to any wavelength.

The advanced very high resolution radiometer (AVHRR) senses clouds and surface temperatures. It stores its data on magnetic tape and transmits them on command to surface receiving stations. It also transmits both low- and high-resolution images in real time. The first AVHRR was launched in October 1978 on the *TIROS-N* (TELEVISION AND INFRARED OBSERVATION SATELLITE) satellite. It transmitted on four channels. Other four-channel AVHRRs were carried on *NOAA 6* and other even-numbered satellites in the NOAA (*see* NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION) series. The first five-channel AVHRR was launched in June 1981 on *NOAA 7* and others on subsequent odd-numbered NOAA satellites. The five channels are: 0.58–0.68 μm (visible part of the spectrum); 0.725–1.10 μm (near-infrared); 3.55–3.93 μm (intermediate infrared); 10.3–11.3 μm and 11.5–12.5 μm (thermal infrared on *NOAA 7* and 9); and 10.5–11.5 μm and 11.5–12.5 μm (thermal infrared on *NOAA 11*).

The scanning multichannel microwave radiometer (SMMR) was carried on the SEASAT and *Nimbus-7* satellites (*see* NIMBUS SATELLITES). It first went into service in 1978 and continues to transmit valuable data from Nimbus. It carries six radiometers with 10 channels delivering measurements at five microwave wavelengths (0.81, 1.36, 1.66, 2.8, and 4.54 cm). The SMMR measures SEA-SURFACE TEMPERATURE, WIND SPEED, WATER VAPOR, clouds and cloud content, snow cover, the type of SNOW, rainfall rates, and different types of ice. It also measures the concentration and extent of sea ice. It has provided detailed information about El Niño events (*see* ENSO) since the 1982–83 El Niño, and it is used to monitor changes in sea ice.

Multichannel sea surface temperature (MCSST) is a procedure in which sea-surface temperatures are calculated from data received from an advanced very high resolution radiometer. First the data are checked to identify points referring to clouds or AEROSOLS; these are removed. Using the remaining data, sea-surface temperatures are calculated by an ALGORITHM such as:

$$SST = a_0 + a_1T_1 + a_2T_2$$

where T_1 is the AVHHR brightness temperature at the waveband 3.55–3.93 μm, T2 is the brightness temperature at the waveband 10.3–11.3 μm or 10.5–11.5 μm depending on the channel used, and a_0, a_1, and a_2 are coefficients that convert the T values into sea-surface temperatures.

The cryogenic limb array etalon spectrometer (CLAES), carried by the UPPER ATMOSPHERE RESEARCH SATELLITE, measures infrared radiation emitted from the atmosphere. Its etalon (*see* INTERFEROMETER) is kept chilled (cryogenic). The instrument measures the temperature in the stratosphere and lower mesosphere (*see* ATMOSPHERIC STRUCTURE) and the trace constituents of the atmosphere: OZONE (O_3), nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), nitric acid (HNO_3), dinitrogen pentoxide (N_2O_5, *see* NITROGEN OXIDES), METHANE (CH_4), CFC-11 (CCl_3F), CFC-12 (CCl_2F_2), and $ClONO_2$.

The wind imaging interferometer (WINDII) carried on the Upper Atmosphere Research Satellite measures the DOPPLER EFFECT on the spectral lines emitted by airglow emissions and aurorae (*see* OPTICAL PHENOMENA), from which it calculates temperatures and winds in the thermosphere (*see* ATMOSPHERIC STRUCTURE).

The electrically scanning microwave radiometer (ESMR) is a radiometer transmitting in the microwave waveband that was launched on the *NIMBUS 5* satellite in December 1972 and continued to function until the end of 1976. Its purpose was to monitor sea ice. It operated on a single channel, collecting data at a wavelength of 1.55 cm. At this wavelength WATER has an emissivity of about 0.44, but the emissivity of ice is between 0.80 and 0.97, so the rate of emission is much greater for sea ice than for water.

The geostationary Earth radiation budget (GERB) is an instrument carried on MSG *(see* METEOSAT) satellites that will observe and measure the radiation reflected and emitted by the Earth.

The high resolution Doppler interferometer (HRDI) is an interferometer carried on the Upper Atmosphere Research Satellite. It measures the Doppler effect on sunlight that is scattered in the stratosphere and on airglow emissions in the mesosphere. From this it provides data on the temperature and winds throughout much of the stratosphere (but with a gap in the upper stratosphere) and most of the mesosphere.

The improved stratospheric and mesospheric sounder (ISAMS), carried on the Upper Atmosphere Research Satellite, measures the temperature in the stratosphere and mesosphere. It also measures concentrations of the atmospheric gases: ozone (O_3), nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), nitric acid (HNO_3), dinitrogen pentoxide (N_2O_5), water vapor (H_2O), methane (CH_4), and carbon monoxide (CO).

The microwave limb sounder (MLS) is carried on the Upper Atmosphere Research Satellite. It is a spectrometer that measures in the microwave waveband and detects concentrations of ozone (O_3), water vapor (H_2O), and chlorine monoxide (ClO) in the stratosphere, and O_3 and H_2O in the mesosphere.

The microwave sounding unit (MSU) is carried on the *TIROS-N* series of NOAA satellites. An MSU measures the emissions of microwave radiation from molecular oxygen in the troposphere. The resultant readings are used to calculate atmospheric temperature with an estimated accuracy of ±0.01°C (±0.02°F). The satellites are in polar orbits that pass over every part of the surface of the Earth several times every day. The continuous record of atmospheric temperature measured by the MSUs began in January 1979.

For many years the MSU data showed no significant rise in the temperature of the atmosphere, in contrast to the rise detected by surface stations. It was eventually found that certain features of the satellite orbit had introduced errors into the readings. These were finally resolved, and when the MSU and surface measurements were reconciled, they showed that a steady rise in atmospheric temperature was occurring at a rate of 2.16°F–3.42°F (1.2°C–1.9°C) per century. This rate of warming agrees with the estimate by the INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE of 3.15°F (1.75°C) per century.

The multispectral scanner carried on LANDSAT satellites obtains images of the Earth's surface with a spatial resolution of 24 feet (80 m). It is used to monitor surface changes, for example in vegetation, coastlines, ICE SHEETS, GLACIERS, and VOLCANOES.

The near-infrared mapping spectrometer is an instrument carried on some satellites that takes readings in the near-infrared part of the SOLAR SPECTRUM. The chemical composition, structure, and temperature of the atmospheres of planets and satellites can be calculated from the data that are produced, as well as details of the mineral and geochemical composition of the surface.

A scatterometer is an instrument that measures the SCATTERING of RADAR waves by the small capillary waves (*see* WAVE CHARACTERISTICS) on the ocean surface. The speed and direction of the surface wind can be calculated from these measurements.

The special sensor microwave imager (SSM/I) is carried on the satellites *DMSP F-8, F-10, F-11, F-12,* and *F-13* belonging to the Defense Meteorological Satellite Program. The SSM/I is a passive microwave radiometer with seven channels and operating at four frequencies (19.35 GHz, 22.235 GHz, 37.0 GHz, and 85.5 GHz). It collects linearly polarized microwave radiation and measures the surface brightness over land and sea. This provides data on clouds and other meteorological phenomena, primarily in support of U.S. military operations, but declassified so they are available to meteorologists. The instruments are carried in a nearly circular, Sun-synchronous, nearly polar orbit with a period of 102 minutes, at a height of 534 miles (860 km) and an inclination of 98.8°.

The stratospheric aerosol and gas experiment (SAGE) comprises a set of instruments carried on the EARTH RADIATION BUDGET SATELLITE that are used to measure the material injected into the stratosphere by volcanoes. The second set of instruments (SAGE-II) was launched in October 1984. SAGE-III was launched in 1999 on the EARTH OBSERVING SYSTEM satellite. As well as aerosols and volcanic gases such as sulfur dioxide, these versions also measure ozone, nitrogen dioxide, and water vapor.

The thematic mapper (TM) is a sensing device carried on the *Landsat 4* and *Landsat 5* satellites in Sun-synchronous orbits. It detects reflected visible and near-infrared radiation and obtains information about the surface of the Earth with a resolution of 100 feet (30 m), producing images that are detailed enough to show individual fields. All TM transmissions from *Landsat 4* ended in August 1993 due to failure of the equipment and some *Landsat 5* transmissions ended in February 1987, also due to failure.

The total ozone mapping spectrometer (TOMS) is the instrument that provided the first satellite evidence of the depletion of stratospheric ozone over Antarctica. It was launched on October 24, 1978, on board the *Nimbus-7* satellite and transmitted daily maps of ozone distribution until 1993. A second TOMS, TOMS-METEOR, was launched in 1991 on the Russian METEOR satellite and a third, TOMS-ADEOS, in 1996 on a Japanese satellite. Although satellites carry other instruments that measure ozone concentrations, the data from TOMS are the most detailed.

TOMS consists of an instrument directed vertically downward that measures the intensity of radiation being reflected upward from the ground or ocean surface or from cloud tops. It samples radiation at six

ULTRAVIOLET (UV) (*see* ULTRAVIOLET INDEX) wavelengths between 312.5 nanometers (nm) and 380 nm in a repeating sequence. UV absorption varies according to the wavelength, so by comparing the amount reflected at each of the wavelengths it is possible to calculate the amount of UV that is being absorbed in the atmosphere. Since it is ozone that absorbs UV at UV-B wavelengths, the density of ozone in the column of air directly beneath the TOMS can be inferred from the amount of UV absorbed.

Wefax is an abbreviation for "weather facsimile," which is a system for transmitting by radio such material as graphic reproductions of weather maps, summaries of temperatures, and cloud analyses. Most Wefax transmissions are from GEOSTATIONARY OPERATIONAL ENVIRONMENTAL (GOES) satellites. Schools and individual enthusiasts can receive Wefax data provided they have suitable equipment.

saturated adiabatic reference process An idealized representation of the way moist air behaves that is used as a standard, or reference, with which events in the real atmosphere can be compared. In fact, it is a fairly accurate description of what usually happens.

The reference process assumes that rising air that is cooling adiabatically (*see* ADIABAT) and is saturated remains very close to SATURATION. WATER VAPOR begins to condense when the temperature of the rising air falls to its DEW point temperature. CONDENSATION releases LATENT HEAT, which sustains the BUOYANCY of the air. As the air continues to rise, its temperature also continues to fall. This chills the air between CLOUD DROPLETS sufficiently to cause the condensation of excess water vapor, maintaining the air at saturation. It is assumed that the moisture condenses as liquid, not ice. This is realistic. In real clouds, water droplets often remain liquid until the temperature falls below about -13°F (-25°C, *see* SUPERCOOLING).

The process is reversible. As the temperature of subsiding air rises, the resulting EVAPORATION of droplets adds enough water vapor to the air to maintain it at saturation. This is close to the process that has been observed in the downdrafts of cumulonimbus clouds (*see* CLOUD TYPES).

saturation The condition in which the moisture content of the air is at a maximum. If additional WATER molecules enter saturated air, then an equal number must leave it, by condensing into liquid water or being deposited as solid ICE (but *see* SUPERSATURATION).

Over the surface of water, water molecules are constantly escaping into the air by evaporation. Once in the air, they add to the vapor pressure (*see* WATER VAPOR). As they move through the air, a proportion of the water molecules will strike the surface of the liquid water. Their energy of motion (KINETIC ENERGY) will be absorbed by the relatively denser mass of water molecules composing the liquid, and the impacting molecules will no longer possess the energy needed to escape into the air. They will enter the water mass. Molecules also escape from and merge with an ice surface in the same way (*see also* SUBLIMATION and DEPOSITION).

As evaporation continues, the vapor pressure increases in the air above the water surface. Eventually, however, a point will be reached at which the number of water molecules evaporating from the liquid surface every second precisely balances the number recondensing into it over the same period. The amount of water vapor present in the air cannot increase beyond this point. The vapor pressure at which this occurs is known as the SATURATION VAPOR PRESSURE, and at the saturation vapor pressure the air is said to be saturated.

Strictly speaking, it is not the air that is saturated, but the water vapor. This is easier to understand if the air is likened to a dry sponge onto which water is sprinkled. As they fall, the water drops disappear into the sponge, which grows steadily moister. Continue with this for long enough and all the tiny air spaces in the sponge will be filled with water. The sponge can then hold no more, and water will start to drip out of it. This has no effect whatever on the material from which the sponge is made—it is the millions of air spaces that are filled with water. These lie between the cells or inside the bubbles that make up the foam, but they are not the solid matter of the sponge itself. Consequently, it is the water that is saturated, and not the sponge. Similarly, atmospheric water vapor comprises molecules that move among the other molecules of the air and the dry air is entirely unaffected by their presence. It is usual, however, to think of the air as being saturated.

Raising the TEMPERATURE of the water molecules increases their kinetic energy. In practice, collisions between air molecules and molecules of water vapor ensure they all have much the same kinetic energy. Water molecules therefore acquire more energy as the air temperature increases. This increases the ease with which they are able to escape from the liquid surface, so the quantity of water vapor increases until a new balance is reached at the higher temperature, with a raised saturation vapor pressure. The result is that the quantity of water vapor that air can hold increases with temperature. In fact, it does so extremely rapidly. Air at 80°F (27°C) holds more than four times the amount of water vapor air at 40°F (4°C) can hold.

The difference between the actual vapor pressure and the saturation vapor pressure at the same temperature is called the saturation deficit, also known as the vapor-pressure deficit. This is also the amount of water vapor, usually measured in grams per cubic meter (g/m^3), that must be added to the air to bring it to saturation at the existing temperature and pressure.

saturation vapor pressure The vapor pressure at which the WATER VAPOR in the layer of air immediately above the surface of liquid water is saturated at a given temperature. The table top right gives a number of representative values. The table shows that as the air temperature increases, the amount of water vapor needed to saturate the air also increases, demonstrating the relationship between the temperature of air and its capacity to hold water vapor. Saturation vapor pressure reaches sea-level atmospheric pressure (1013 mb; 101.3 kPa) at 212°F (100°C).

The saturation vapor pressure over an ICE surface is lower than that over the surface of liquid water supercooled (*see* SUPERCOOLING) to the same temperature, because the stronger bonds between water molecules in ice reduce the rate at which they enter the air by SUBLIMATION. As a result, air over an ice surface holds less water vapor than air over a liquid surface at the same temperature.

The Clausius–Clapeyron equation relates the saturation vapor pressure (e_s) to the absolute temperature (T). The equation is:

$$de_s/dT = L/T(\alpha_2 - \alpha_1)$$

where L is the LATENT HEAT of vaporization, α_2 is the SPECIFIC VOLUME of water vapor and α_1 is the specific volume of liquid water. Since α_2 is usually very much larger than α_1, α_1 can be ignored.

Saturation Vapor Pressure

Temperature °F (°C)	Pressure mb (Pa)
-58 (-50)	0.039 (3.94)
-40 (-40)	0.128 (12.83)
-22 (-30)	0.380 (37.98)
-4 (-20)	1.032 (103.2)
14 (-10)	2.597 (259.7)
32 (0)	6.108 (610.78)
50 (10)	12.272 (1227.2)
68 (20)	23.373 (2337.3)
86 (30)	42.430 (4243.0)
104 (40)	73.777 (7377.7)

scalar quantity A physical quantity that either does not act in a particular direction, as in the case of TEMPERATURE, or for which the direction of action is unimportant or not specified, as in the case of speed. This is contrasted with a VECTOR QUANTITY, in which the direction of action must be specified.

scale height The thickness the atmosphere would have if its DENSITY were constant throughout at its sea-level value of 1.23 kg/m^3. The scale height is 8.4 km (5.2 miles).

scattering The result of the reaction that occurs when visible light (*see* SOLAR SPECTRUM) passes through the atmosphere and collides with air molecules and AEROSOL particles. The light changes direction repeatedly due to the combined effects of DIFFRACTION, REFLECTION, and REFRACTION. Molecules and very small aerosol particles, with sizes smaller than the wavelength of the light, also absorb the radiation. They are excited by it and reradiate it in all directions.

The size of molecules and particles in relation to the wavelength of light is known as the size parameter (X) and is given by:

$$X = \pi d/\lambda$$

where d is the diameter of the molecule or particle and λ is the wavelength of the light. Air molecules and the smallest aerosol particles are much smaller than the wavelength of light (d is smaller than λ), so X is less than 1. The smaller they are, the less efficiently bodies scatter radiation, and their efficiency decreases as the difference between their size and the wavelength increases. The efficiency of scattering is inversely proportional to the fourth power of the wavelength (λ^{-4}). This means that the shorter wavelengths are scattered most efficiently.

As light passes through the upper atmosphere, the shortest visible wavelengths of 0.4–0.44 μm, which correspond to violet and indigo light, are scattered first. Each time violet or indigo radiation strikes a molecule or particle it rebounds in a random direction. This happens repeatedly, the amount of scattering increasing with the distance the radiation travels through the air. Violet and indigo radiation is scattered so thoroughly that it contributes very little to the sky color. The sky is not violet or indigo.

Blue light is scattered next. Because the efficiency of scattering is proportional to λ^{-4}, blue light (0.44–0.49 μm) is approximately nine times more likely to be scattered than red light (0.64–0.7 μm). By the time sunlight reaches an observer at the surface, the blue light has been scattered in all directions so that the clear sky appears blue in all directions.

At sunrise and shortly before sunset, the Sun is low in the sky, and its light travels through a much thicker layer of atmosphere before reaching the surface. If the sky is clear, the distance is sufficient for all the blue and green light to be scattered, so it disappears, but the longer distance also means there is a greater chance for light at longer wavelengths to be scattered, because the light encounters more air molecules. The blue and green light having been removed, the scattered light that penetrates to the surface is orange and red. This accounts for the colors of the sky at dawn and sunset.

At night the sky is conventionally described as being black. In fact, scattering of starlight continues and the sky is really a very deep shade of blue, aptly named midnight blue.

Bigger particles, for which X is greater than 1 (d is greater than λ), scatter light much more efficiently. When the relative HUMIDITY is high, small aerosol particles absorb water vapor and expand. As they grow larger, the amount of light they scatter increases. They scatter all wavelengths equally, and so the scattered light is not separated into its constituent colors. The scattered light is white, and as scattering increases the sky becomes whiter and hazier. HAZE reduces VISIBILITY, and it can turn into FOG if the relative humidity reaches 100 percent and water starts to condense onto the particles.

Scattering by molecules and very small aerosol particles was first observed experimentally by John Tyndall (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). Lord Rayleigh (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), however, discovered the reason and showed that radiation is scattered most when the molecules and particles are smaller than the wavelengths of radiation being scattered. Consequently, this is known as Rayleigh scattering. A Rayleigh atmosphere is an idealized atmosphere that consists only of molecules and particles that are smaller than about one-tenth the wavelength of the solar radiation passing through it. In such an atmosphere, the radiation would be subject only to Rayleigh scattering.

Scattering by larger particles is known as Mie scattering. This occurs when the radiation interacts with particles of a size similar to the wavelength of the radiation. Diffraction, reflection, and refraction combine to cause the change in direction. Mie scattering is predominantly in a forward direction, and all wavelengths are affected. The German physicist Gustav Mie (1868–1957, *see* APPENDIX I: BIOGRAPHICAL ENTRIES) was the first person to describe this process in detail, in 1908.

The scattering of all wavelengths of radiation equally as the radiation passes through the atmosphere is called nonselective scattering. It is caused by particles that are bigger than the wavelength of the radiation. Because all wavelengths are scattered equally, nonselective scattering produces a white sky.

Afterglow is a bright arch that appears in the west above the highest clouds just after sunset. It is caused by the scattering of light by DUST particles suspended in the upper troposphere.

Airlight is light that is scattered toward an observer by aerosols or air molecules lying between the observer and more distant objects. This light is visual NOISE that makes the more distant objects less clearly visible, thereby reducing visibility. The appearance of a cloudless sky in daytime is due entirely to airlight. At dawn the amount of airlight increases, and it is this that obscures the stars, rendering them invisible. At sunset, as the amount of airlight diminishes, the stars reappear.

Alpine glow is a series of colors that are sometimes seen over mountains in the east, especially if the mountains are covered with snow, as the Sun is setting in the west, and over mountains in the west as the Sun is rising in the east. The phenomenon is caused by the scattering of light reflected from the mountains. The colors change from yellow to orange to pink to purple at sunset and in the reverse order at sunrise.

scavenging The removal of particulate matter (*see* AIR POLLUTION) from the air by the action of PRECIPITATION. The natural processes involved are rainout (*see* CLOUD CONDENSATION NUCLEI), snowout (*see* SNOW), and washout (*see* RAINDROPS).

These processes remove most particles within hours or at most days from the time they enter the air (*see* RESIDENCE TIME). The term is also applied to the removal of gaseous pollutants as a result of chemical reactions. These most commonly involve free radicals, such as hydroxyl (OH).

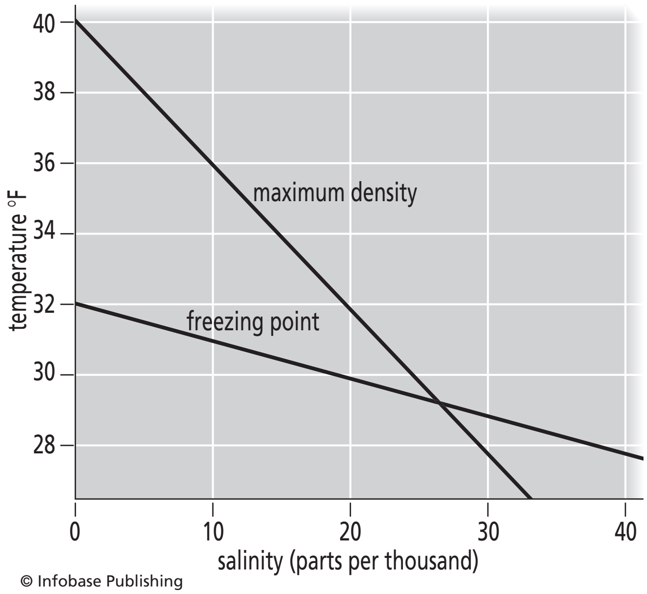
sclerophyllous plant A sclerophyllous plant is one that is adapted to prolonged periods of hot, dry weather. The Greek word *skleros* means "hard" and *phullon* means "leaf." Sclerophyllous plants have leaves that are small, thick, hard, and leathery. They are also evergreen, which means they are not all shed at the same time and the plant retains leaves through the year.

Holly (*Ilex* species), holm (or holly) oak (*Quercus ilex*), and California lilac (*Ceanothus* species) are sclerophyllous plants with broad leaves, as are the gum trees (*Eucalyptus* species) native to Australia. Many pine trees (*Pinus* species) are also sclerophyllous.

Further Reading

Allaby, Michael. *Temperate Forests*. Rev. ed. Ecosystem. New York: Facts On File, 2007.

sea ice Ice that forms by the freezing of sea water is called sea ice. When the TEMPERATURE at the sea surface is below 32°F (0°C) and the sea is calm, SNOW falling on the sea may settle and accumulate. It is able to do so because snow consists of freshwater, which has a higher freezing temperature than salt water. Ice may also be carried to the sea by rivers or reach it by breaking away from GLACIERS to form ICEBERGS. Although these may float on the sea, accumulated snow and ice that originated on land are not counted as sea ice. That term is reserved for ice resulting from the freezing of the sea itself.



The freezing point of seawater varies according to the salinity of the water. As seawater freezes, the salinity of the surrounding water increases, raising its density.

WATER freezes at 32°F (0°C) at average sea-level atmospheric pressure, but only if it is pure H_2O. If other substances are dissolved in it, the freezing temperature is lower by an amount proportional to the strength of the solution. The average salinity of seawater, measured as all the dissolved salts but consisting mainly of sodium chloride (NaCl), is 35 grams per kilogram. This is the same as 35 parts per thousand (because 1 g = 1/1,000 kg) and is written as 35‰ (pronounced "per mil"). At 35‰ salinity, the freezing point of water is 28.56°F (-1.91°C). If the sea-surface temperature is between 32°F and 29°F, the seawater will not freeze, but SNOW falling onto it will not melt.

When the temperature falls below freezing, ICE CRYSTALS will start to form. These will consist of pure water. The dissolved salt will be excluded from the crystals. This will increase the salinity of the water adjacent to each crystal, lowering its freezing point still more, but also increasing the DENSITY of the water by an amount equal to that of the salt molecules that are added to it. The denser water will sink, and less dense water will rise from below to replace it, so freezing at the surface increases the rate at which water mixes in the uppermost layer of the sea (*see* THERMOHALINE CIRCULATION).

Provided the sea temperature remains below freezing, ice crystals will continue to form until they cover large areas of the surface. This is known as frazil ice. Frazil ice dampens down small wave movements, which makes the water appear oily, and as freezing continues and more ice crystals form, the sea becomes covered with slush.

As the process continues, the frazil ice thickens, becoming grease ice, and then breaks into pieces due to the motion of the sea. The pieces jostle against one another, which gives them a rounded shape. They are then known as pancake ice. Pancake ice consists of fairly thin patches of ice. These constantly collide with one another, and their circular shape results from the collisions.

As pancake ice forms, salt water becomes trapped between ice crystals, so that although the ice itself consists of only pure water, the pancake ice has salt within it. How much salt becomes trapped in this way depends on the speed with which the ice forms and, therefore, on the air temperature. When the air temperature remains at about 3°F (-16°C) while the ice is forming, the salinity of pack ice is approximately one-fifth that of the seawater (7‰) and at -40°F (-40°C) it is roughly one-third (12‰).

Pack ice comprises large blocks of ice that cover the surface of the sea. In winter, pack ice covers about 50 percent of Antarctic water and about 90 percent of Arctic water, although the area covered by sea ice in the Arctic has been decreasing, probably due mainly to the phase of the ARCTIC OSCILLATION that prevailed through much of the 1990s. In summer, ice covers about 10 percent of the sea in the Antarctic and about 80 percent in the Arctic. The percentage of an area of ocean surface that is covered by ice is called the ice concentration. An ice concentration of 0 percent means there is no ice; an ice concentration of 50 percent means half the area is covered; an ice concentration of 100 percent means the area is fully covered. Close pack ice has an ice concentration of 70–80 percent, with most of the floes in contact. Open pack ice has an ice concentration of 40–60 percent.

Ships can usually move through pack ice if it covers less than 75 percent of the surface and there is open water between blocks. A stretch of open water big enough for a ship to pass is called a lead. An irregular area of open water that is surrounded by sea ice is called a polyn'ya (plural polynyi). Polynyi may contain brash ice or young ice The presence of pack ice can be detected from a distance by the appearance of ice blink (*see* OPTICAL PHENOMENA).

When the blocks of pack ice unite to form a complete ice cover, they are known first as young ice, then as winter ice, and eventually as polar ice. Young ice is a layer of ice that is less than one year old and that forms a complete covering on a large area of the surface of the sea with a thickness of more than about 2 inches (5 cm). Winter ice is a layer less than one year old that forms a complete covering on a large area of the surface of the sea with a thickness of more than 8 inches (20 cm). Polar ice is a layer that forms a complete covering on a large area of the surface of the sea and that is more than one year old.

Floes are flat pieces of ice. A floe that is 6.5–330 feet (2–100 m) across is called a small floe. A medium floe is 330–1,600 feet (100–500 m) across, a big floe is 0.3–1.2 miles (0.5–2 km) across, and a giant floe is more than 6 miles (10 km) across. A vast floe is 1.3–6 miles (2–10 km) across.

Polar ice is less saline than winter ice and young ice, because in summer, when the ice partly melts, the spaces in which salt water are trapped open, allowing salt to drain away. Salinity is lowered further as a consequence of the low thermal conductivity of ice. This insulates the water below the ice, preventing its temperature from falling and so decreasing the rate at which ice accumulates on the underside of the surface layer. At the same time, snow falling onto the surface of the ice remains there, diluting the salt content of the ice as a whole.

Submerged ice that is firmly attached to the seabed is called anchor ice. Brash ice comprises fragments of broken ice not more than about 6 feet (1.8 m) across.

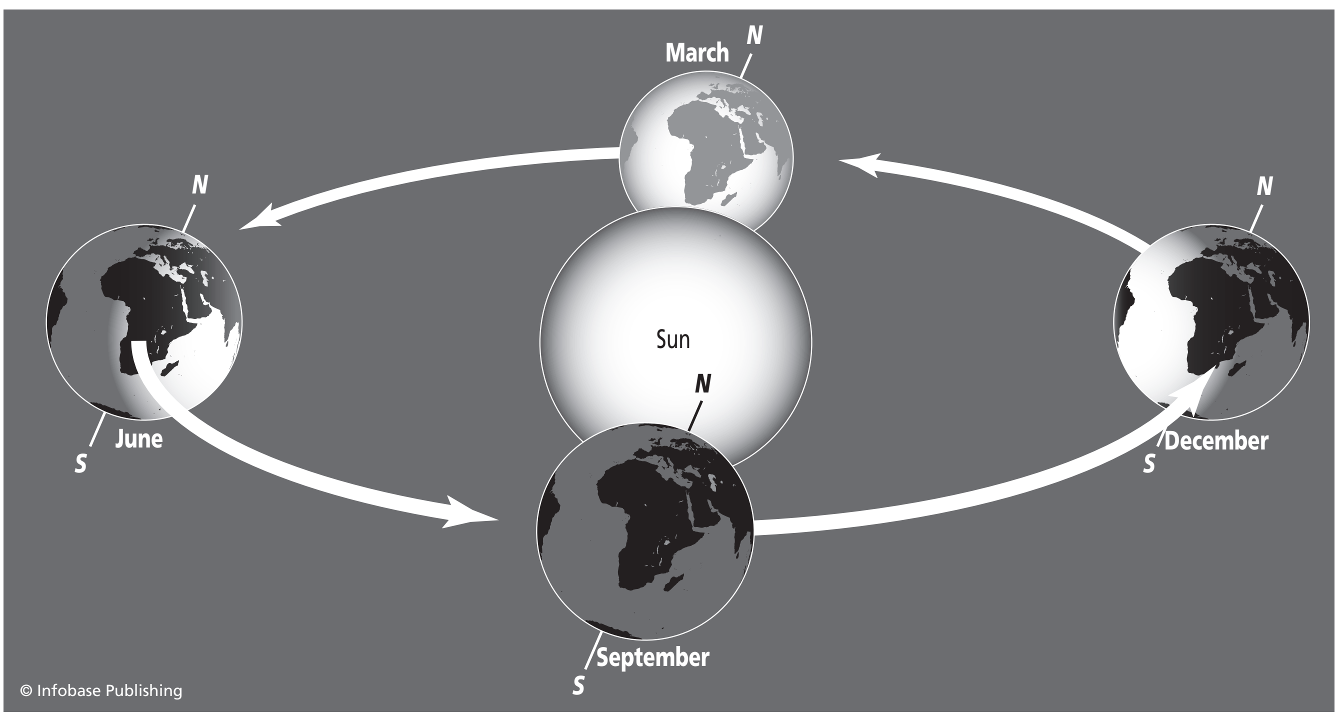
Seasat The first satellite that used imaging RADAR to study the Earth. It was equipped with a scatterometer and with a scanning multichannel microwave radiometer (*see* SATELLITE INSTRUMENTS). *Seasat-A* was launched on an Atlas–Agena rocket from Vandenberg Air Force Base, California, on June 26, 1978, into a slightly elliptical polar ORBIT at a height of 482–496 miles (775–798 km). Its orbit carried it over nearly 96 percent of the surface of the Earth every 36 hours. On October 10, after transmitting data for 106 days, a short circuit drained all the power from its batteries and the satellite ceased to function.

seasons In summer, the days are long, the nights short, and the weather is relatively warm. In winter, it is the opposite. Days are short, nights are long, and the weather is relatively cold. These variations in weather conditions define the seasons—the four periods of equal length we know as spring, summer, fall or autumn, and winter.

This description is true only in latitudes outside the TROPICS, however, and even there in some places the difference in temperature between one season and another is much less important—or marked—than the difference in rainfall. In these regions, the names "summer" and "winter" are replaced by "rainy season" and "dry season." In low latitudes, spring and fall are short, or barely happen at all. Nor does the change in day length affect all places equally. At the summer SOLSTICE, for example, people at the equator experience 12 hours of daylight, while those at the North and South Poles experience 24 hours. At the winter solstice, people at the equator still experience 12 hours of daylight, but for those at the Poles the Sun does not rise at all and they have 24 hours of darkness, or to be more precise, of twilight. Although the Sun remains below the horizon, the atmosphere refracts and reflects some of its light over the horizon.

There are few places on Earth where no seasonal changes at all occur in day length, mean TEMPERATURE, or rainfall, but the seasons become more strongly differentiated with increasing distance from the equator. That is because the amount of solar radiation received at the surface changes through the year as a consequence of the tilt in the rotational axis of the Earth with respect to the PLANE OF THE ECLIPTIC.

Instead of being normal (at right angles) to the plane of the ecliptic, the Earth's axis is at an angle of 66.55° to it, so it is tilted 23.45° from the normal. As the Earth moves along its orbital path, first one hemisphere and then the other is tilted toward the Sun. This produces four clearly defined positions. In two of them, known as the solstices, one hemisphere receives maximum exposure to sunlight and the other receives minimum exposure. In the others, known as the EQUINOXES, both hemispheres are equally exposed. Seen from a position on the equator, at the equinoxes the Sun is directly over head at noon and at the solstices it is at an elevation of 66.55° above the horizon at noon, or 23.45° from the vertical, displaced either to the north or to the south. At the solstices, the Sun is directly overhead at one or other of the Tropics.



Because the rotational axis of the Earth is tilted in respect to the plane of its solar orbit, in June the Northern Hemisphere receives more solar radiation than the Southern Hemisphere and in December the situation is reversed. This produces the seasons.

The change in angle alters the ANGLE OF INCIDENCE of solar radiation, and this in turn alters the intensity of the radiation that is received at each unit area of the surface. Because the Earth is almost spherical in shape, the angle of incidence increases with latitude and so, therefore, does the intensity of radiation per unit area at the surface. It is this change that causes mean temperatures to be higher in summer than in winter and higher in low latitudes than in high ones.

sea-surface temperature (**SST**) The TEMPERATURE of the WATER at the surface of the sea, or sea-surface temperature, is routinely measured by drifting buoys, ships, and orbiting satellites. Of these, the satellite observations are the most extensive in their coverage and also the most accurate. Buoys can measure only the temperature of the water around them, which may not be representative of the ocean as a whole, and ships measure the temperature of the water they take on board to cool their engines. Water intakes are located about 16 feet (5 m) below the surface, and so ship measurements must be corrected to give the temperature at the surface.

Sea-surface temperature is climatically important because it affects the temperature of the air immediately above the surface and the EVAPORATION rate of water. This in turn affects air temperature, because WATER VAPOR is the most important greenhouse gas (*see* GREENHOUSE EFFECT), as well as cloud formation, ALBEDO, and PRECIPITATION.

Sea-surface temperatures change with the SEASONS, but they are also subject to other influences. Latitudinally, they change because of the presence of warm and cold ocean currents, and they also rise and fall in fairly regular cycles. Some cyclical variations operate with a period of a few years, others of decades or centuries. There is still much to be learned about these cycles.

EDDIES in ocean currents can produce local variations in sea-surface temperatures. These are similar to atmospheric CYCLONES and ANTICYCLONES, but they persist for months rather than days.

seawater Seawater is the water found in the seas and oceans. It contains an average of 35 parts per thousand (per mil) of dissolved compounds, known collectively as salts.

The proportion of salts determines the salinity of the water, so if water contains 35 per mil of salts, its salinity is 35 per mil. Salinity ranges from 34 per mil to 37 per mil in coastal areas, but may be close to 0 per mil where rivers discharge large volumes of FRESHWATER, or as high as 40 per mil where a large amount of water is lost by EVAPORATION from a partially enclosed body of water, such as the Persian Gulf and Red Sea.

Chlorine (Cl), sodium (Na), sulfur as sulfate (SO_4), magnesium (Mg), calcium (Ca), and potassium (K) together account for more than 99 percent of the dissolved matter present in seawater. The table above lists the major constituents of seawater.

Major Constituents of Seawater

	Parts per thousand	Percentage by weight
Chloride*	19.35	55.07
Sodium	10.76	30.62
Sulfate*	2.71	7.72
Magnesium	1.29	3.68
Calcium	0.41	1.17
Potassium	0.39	1.10
Bicarbonate*	0.14	0.40
Bromide*	0.067	0.19
Strontium	0.008	0.02
Boron	0.004	0.01
Fluoride*	0.001	0.01
Total		99.99

*Chlorine (Cl), bromine (Br), and fluorine (F) are present as compounds with other elements and so are measured as chlorides, bromides, and fluorides. Sulfur is present as sulfate (SO_4^{2-}) compounds. Bicarbonate is HCO_3^-, which is a salt of carbonic acid (H_2CO_3).

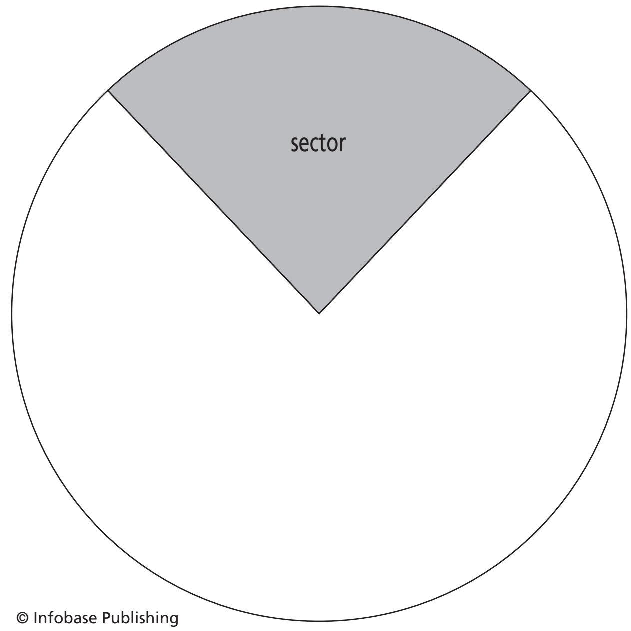
seaweed A plant belonging to any one of several thousand species of multicellular marine algae may be described as seaweed. Some seaweeds are large. Certain species of *Macrocystis* and *Nereocystis,* found in the Pacific and Southern Oceans, grow to more than 100 feet (30 m) in length.

Seaweeds comprise three plant phyla (or divisions), the Rhaeophyta (brown seaweeds), Rhodophyta (red seaweeds), and Chlorophyta (green seaweeds). Seaweeds grow in coastal waters throughout the world, from the uppermost part of the shore reached by spring TIDES to where the water is about 165 feet (50 m) deep.

At greater depths there is insufficient light for PHOTOSYNTHESIS.

Seaweeds have many uses. Some are eaten, others are used to make fertilizer, and some were traditionally used to foretell the weather. The "meteorological" species are adapted to survive the very harsh environment of the upper shore, where they are alternately submerged in SEAWATER and exposed to the air and warm sunshine. They survive the dry conditions by shriveling and becoming brittle, but as soon as they detect moisture they begin to absorb water and revive. The wracks are the weeds that demonstrate this capacity best. These are brown seaweeds of the genera *Fucus* and *Ascophyllum,* such as bladder wrack (*F. vesiculosus*) and knotted wrack (*A. nodosum*).

People used to bring these seaweeds home from the shore and hang them outside the door. If the seaweed was dry and shriveled the weather would be fine, but if it became flexible and rubbery it meant rain was likely. The method worked, but only up to a point, because by the time the seaweed responded to the rise in HUMIDITY the change in the weather was usually self-evident.



A sector is a plane surface bounded by two radii and an arc of a circle.

SeaWinds A RADAR instrument that is carried on board the QUIKSCAT satellite. SeaWinds was launched on June 19, 1999, and collects data from a continuous band, 1,118 miles (1,800 km) wide, covering 90 percent of the Earth's surface and making approximately 400,000 measurements in a day.

SeaWinds has a rotating dish antenna with two spot beams that sweep in a circular pattern radiating microwave pulses at 13.4 gigahertz. It gathers data on low-level wind speed and direction over the oceans and also tracks the movement of Antarctic ICEBERGS. The data is used in scientific studies of global climate change and weather patterns, interactions between the atmosphere and the ocean surface, to track changes in tropical rain forests, and to monitor movements at the edge of the Antarctic SEA ICE and pack ice.

Further Reading

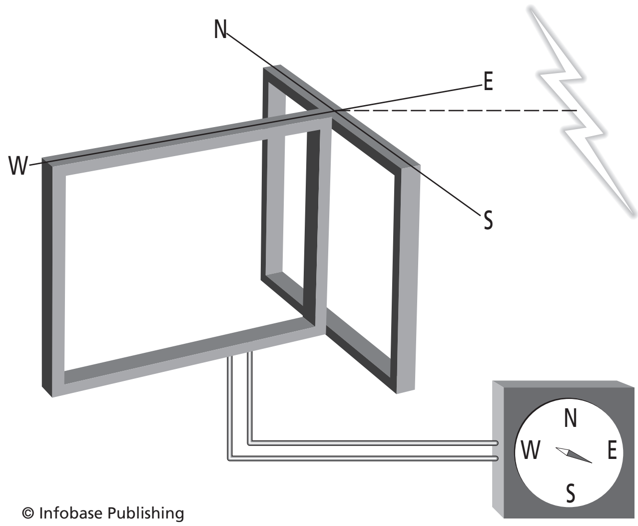
NASA, "SeaWinds Wind Report." Available online. URL: http://haifung.jpl.nasa.gov/. Accessed January 27, 2006.

sector A horizontal plane that is bounded on two sides by the radii of a circle and on the third side by an arc that forms part of the circumference of the same circle. A warm sector (*see* FRONT) is an area that is approximately of this shape, and bounded on two sides by a warm front and a cold front, although there is no arc bounding it on the third side.

serein Rain that falls from a clear sky is called serein. The word is derived from the Latin *serum,* which means "evening," and serein is a fine rain that falls at evening in the TROPICS.

There are several possible explanations for this very rare phenomenon. CLOUD DROPLETS may evaporate after very small RAINDROPS have started to fall. Because of their size, the drops take several seconds to reach the ground, and by the time they do so the cloud has dissipated. Alternatively, the cloud may move away while the raindrops are falling, so that by the time they reach the ground the cloud is no longer overhead. It may also happen that the wind blows fine rain so that it reaches the ground at a point that is not beneath the cloud. In this case, however, the rain arrives at an angle and its source is fairly obvious.

Severe Local Storms unit (SELS) A meteorological center, located in Kansas City, Missouri, where severe weather is monitored and forecasts of storms are issued for up to 6 hours ahead.



A sferics receiver has two square aerials at right angles to each other. This arrangement allows the receiver to detect the direction from which a disturbance caused by lightning is coming. The location of the storm can be identified by using two or more sferics receivers.

sferics A word that is derived from "atmo*spherics,*" sferics are the electromagnetic disturbances caused by natural electrical phenomena. They interfere with radio transmissions and can sometimes be heard on a radio as crackling or whistling noises.

LIGHTNING causes sferics, and this is used to locate the source of the THUNDERSTORM. The device uses two square radio receiver aerials mounted at right angles to each other so that one is aligned north–south and the other east–west. The strength of the sferics signal varies according to the angle at which it approaches the aerials. The signal strength is converted to a direction that is displayed on a screen. A sferics receiver can detect a thunderstorm up to a distance of about 1,000 miles (1,600 km).

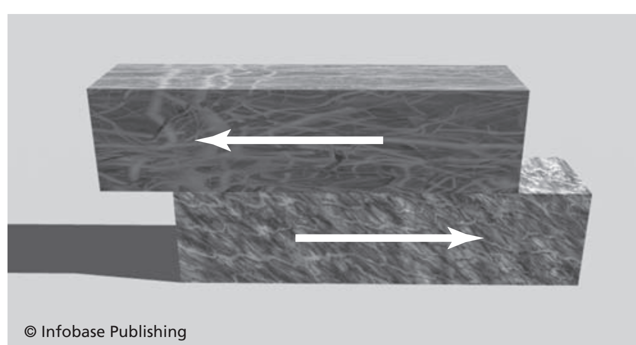
When two or more widely separated sferics receivers detect the same thunderstorm, they can reveal its location. This will be at the intersection of lines drawn on a map from the position of each receiver in the direction it has measured. The position of a storm that is identified in this way is known as a sferics fix, and a report of a storm that is based on measurements by a sferics receiver is called a sferics observation.

shear Shear is a force that acts parallel to a plane, rather than at right angles to it. If two plane surfaces experience a shearing force, one surface is being pushed one way and the other in another (not necessarily opposite) direction.

Fluids as well as solids can experience shear. If two bodies of fluid are in motion, the shearing force acting on them may result in a change in their relative speeds rather than direction. When crossing from one body to the other, the shear is evident as an abrupt change in either the direction or speed of movement, or both. A shear line is a line or narrow belt that marks an abrupt change, or shear, in the direction or speed of the wind.

A shear wave may form where there is strong horizontal wind shear in stable air (*see* STABILITY OF AIR). The difference in wind speed across a boundary between two layers of air causes TURBULENT FLOW. Air from the lower layer rises, but its stability causes it to sink again, establishing a wave pattern. In a vertical rather than horizontal plane, this is the mechanism that causes a flag to flap in the wind. Air is moving at different speeds on either side of the flag. The wind shear generates a wave pattern that is prevented from breaking down by the cloth of the flag, which acts in the same way as the inherent stability of the air in a shear wave. Where the Richardson number falls below the critical value of 0.25, the stability of the air is insufficient to sustain the wave pattern, which breaks down into general turbulence. The breakdown of shear waves plays an important part in transferring energy and transporting materials such as WATER VAPOR to and from the ground surface.

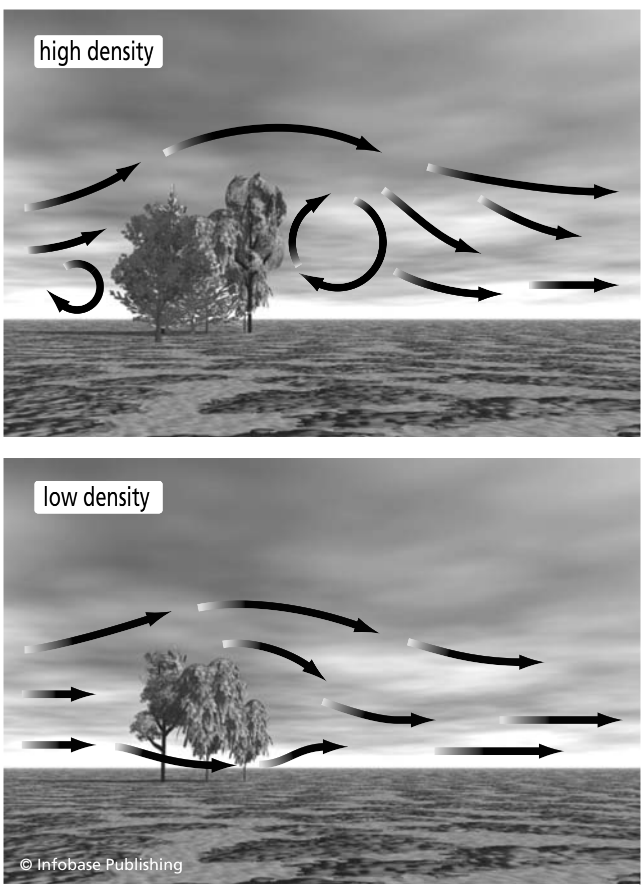
The force exerted on a surface by air that passes across it is called surface shearing stress. Because the force acts on a surface area, surface shearing stress is expressed as a pressure, measured in pounds per square



A shearing force acts parallel to a plane rather than at right angles to it. The arrows represent the direction of shear.

inch or, in SI units (*see* Appendix VIII: SI Units and Conversions) in pascals. The pressure exerted as surface shearing stress is equal to the opposing force of drag that is exerted by the surface on the moving air. Drag slows the air, but its immediate effect is felt only in the layer of air in immediate contact with the surface.

shelter belt A line of trees that is grown at right angles to the prevailing wind (*see* wind systems) in order to reduce the wind speed on the lee side as a means of protecting ground or crops that might be damaged by strong winds. Air approaching the trees is forced to rise. This squeezes the streamlines together, accelerating the air as it passes over the tops of the trees, but the moving air decelerates as soon as it has crossed the barrier. The air then separates from the surface of the trees and forms large eddies that gradually become smaller in the wake (*see* turbulent flow) of the shelter belt. Finally, the air resumes its former movement and speed. A shelter belt (or wall, fence, embankment or other obstacle used for the same purpose) affects the flow of air above and in front of the barrier for a distance equal to three times the height of the barrier.



The trees form a barrier that slows the wind. If the barrier is dense, the wind is slowed greatly, but soon recovers. A low-density barrier slows the wind less, but the effect extends farther.

The effect on the downwind side of the barrier depends on the density of the barrier. If the barrier is very dense, the wind speed is greatly reduced in the large eddy that forms immediately downwind of it, because air cannot penetrate the barrier. The wind speed quickly recovers to about 90 percent of its former value, however, so the effect is limited to a distance about 10–15 times the height of the barrier. If the barrier is less dense, so it allows some of the air to pass through it, no eddy forms. The reduction in wind speed is smaller immediately behind the barrier, but it extends downwind for a distance that is equal to 15–20 times the height of the barrier. A medium-density barrier performs even better. The wind recovers to 90 percent of its original speed about 20–25 times the barrier height downwind, and some shelter belts provide this amount of protection for a distance equal to 40 times their height.

shock wave A shock wave is a traveling wave that moves through a fluid as a narrow band across which the pressure and/or temperature increase abruptly. Any object that moves through air or water generates a disturbance that propagates as a series of shock waves. Any sudden expansion or movement, such as an explosion or earthquake, generates shock waves. Sound waves are also shock waves.

shower A shower is a short period of precipitation that falls from a convective cloud such as cumulus or, more commonly, cumulonimbus (*see* cloud types). A shower is produced when moist, cool, unstable air (*see* stability of air) crosses a warmer surface. Precipitation starts and ends abruptly, varies in intensity but can be very heavy, and is often followed by sunshine and a blue sky. A shower of this type is sometimes called an air mass shower.

When the mechanism sustaining a cumulonimbus cloud fails and the cloud starts to dissipate, there can be a sudden, very intense shower of rain. This is a cloudburst. Individual cloud bursts are usually of brief duration, but they may be repeated, because as one cloud dissipates another forms along a SQUALL line.

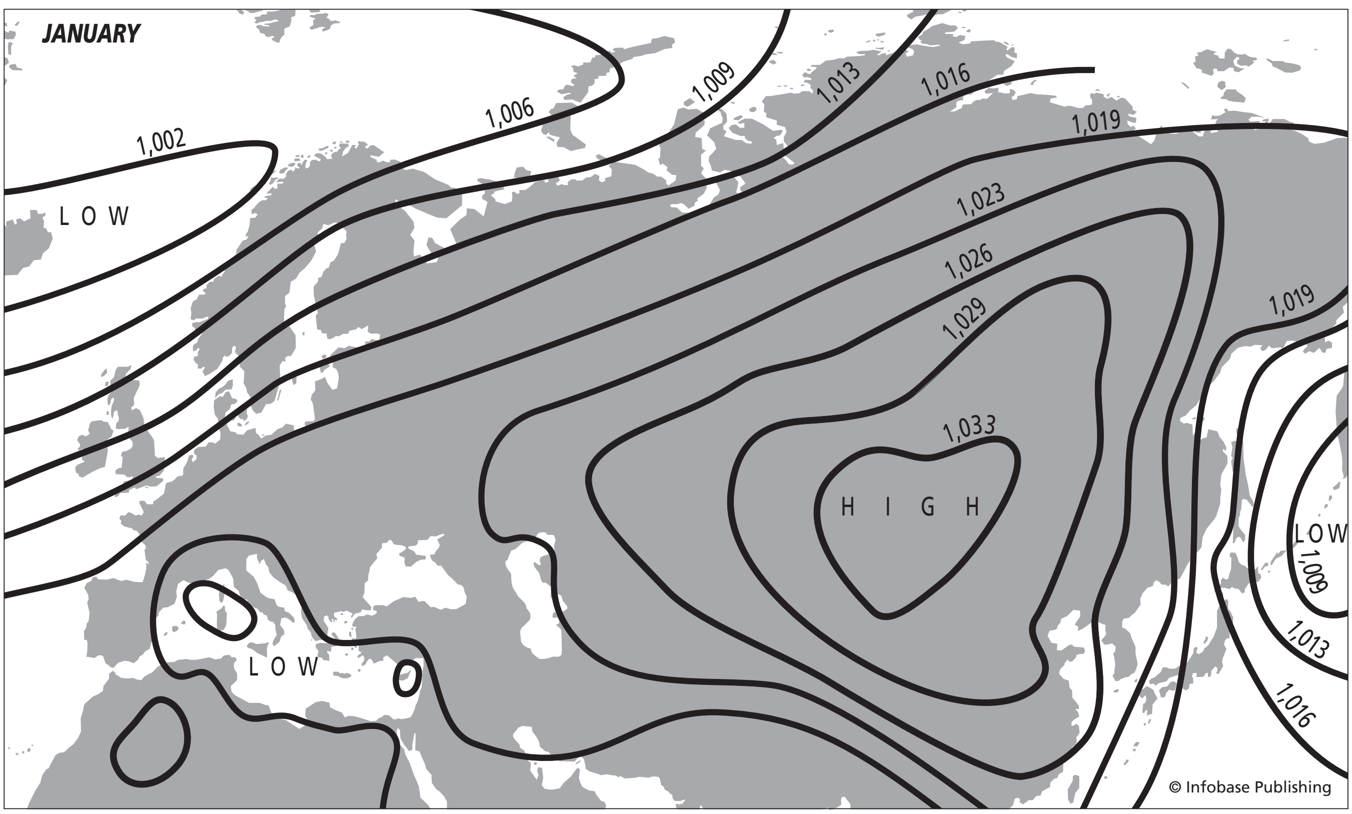
The vertical currents inside a cumuliform cloud carry water droplets upward, and in a large cumulonimbus the updrafts are often strong enough to keep a large amount of water airborne. Eventually, downdrafts inside the cloud overlap and suppress the updrafts. When this happens, the water droplets are no longer supported and the cloud loses all its water at once in the form of a cloudburst. A big, fully developed cumulonimbus may hold 300,000 tons (275,000 tonnes) of water. If that amount of water falls on an area of 10 square miles (26 km^2) it will deliver about 4 inches (10 cm) of rain. Rainfall as intense as this may cause a FLASH FLOOD.

A fog shower is quite different. This is a type of precipitation that can occur on mountains at elevations that are higher than the lifting condensation level (*see* CONDENSATION) when the mountain is engulfed by a passing cumulonimbus or large cumulus cloud that contains supercooled (*see* SUPERCOOLING) water droplets. Supercooled droplets freeze on contact with small objects, producing a coating of rime frost or glaze (*see* ICE). The cloud appears as fog to an observer on the mountainside, and the impact of the very cold droplets feels like a shower of rain.

Siberian high The Siberian high is a region of high surface AIR PRESSURE that forms over Siberia in winter. Centered to the south of Lake Baikal, its influence covers all of Asia north of the Himalayas and extends westward, centered on latitude 50°N, across southern Russia and central Europe as far as the Atlantic.

The high produces a wind divide. The mid-latitude westerlies (*see* WIND SYSTEMS) prevail to its north and northeasterlies prevail to its south, across the steppes from the Ukraine eastward. The northeasterlies bring very dry, continental polar air (*see* AIR MASS).

The Siberian high produces the highest pressures known anywhere on Earth. On December 31, 1968,



The usual distribution of pressure over Eurasia in January shows a large area of intensely high pressure centered on southern Siberia and Mongolia. This is the Siberian high.

a pressure of 1,084 millibars (32.01 inches, 81.31 cm) was recorded at the town of Agata, Russia (66.83°N 98.71°E). This is believed to be the highest pressure ever recorded.

Siderian The earliest period of the PROTEROZOIC era of the Earth's history, which began about 2,500 million years ago and ended 2,300 million years ago. Little is known about the geography or climates of the Earth during this time. *See* APPENDIX V: GEOLOGIC TIMESCALE.

Silurian The final period of the lower PALEOZOIC era of the Earth's history, which began 443.7 million years ago and ended 416 million years ago. Marine life flourished during the Silurian, and fossils from that time were first identified in the 1830s in South Wales by the English geologist Sir Roderick Impey Murchison (1792–1871). Murchison named the period Silurian after the Silures, a Celtic tribe living in Roman times along what is now the border between Wales and England.

The continents were clustered close to the equator during the Silurian, but with Gondwanaland, comprising the southern continents, drifting southward (*see* PLATE TECTONICS). Much of the low-lying land at the equator lay beneath shallow seas. Climates were generally warm, although there were GLACIERS in latitudes higher than about 65°. Some regions in latitudes within 40° of the equator had arid climates. *See* APPENDIX V: GEOLOGIC TIMESCALE.

silver iodide A yellow, solid, compound of silver, silver iodide (AgI) melts at 1,033°F (556°C) and boils at 2,743°F (1,506°C). It is used in CLOUD SEEDING because it can be made to form particles the size of FREEZING NUCLEI.

The material used for cloud seeding is a mixture of silver iodide and another compound, commonly sodium iodide (NaI) dissolved in acetone. The solution is then burned in a propane flame or a flare mounted on an airplane, releasing a smoke. As the smoke cools, the silver iodide solidifies as small crystals. Dropped into a cloud with a temperature of -4°F (-20°C), one ounce of silver iodide produces about 2.8×10^{17} of ice nuclei (10^{15} nuclei per gram of AgI).

singularities Certain types of weather occur fairly regularly at a particular time each year. These recurring events are known as singularities. The Indian summer (*see* WEATHER TERMS) and the sudden advent of ANTICYCLONES at the end of June are probably the best-known examples, but there are many more. The January thaw, affecting the northeastern United States around January 20–23, is a singularity. PRECIPITATION decreases sharply in California in March and April, due to an extension of the PACIFIC HIGH, while at the same time it increases in the Midwest due to an increase in cyclogenesis (*see* CYCLONE) in Colorado and Alberta, and an extension of maritime air (*see* AIR MASS) from the Gulf of Mexico. These are also singularities.

Singularities are major features of WEATHER LORE. Certain months are linked to particular kinds of weather, for example April showers and February fill-dyke (*see* LOCAL WEATHER). Many of these assumed singularities are imaginary, but others are genuine.

European singularities have been intensely studied, and a catalog of them has been compiled. Spring is often dry over much of northern Europe. This is due to a marked reduction in the frequency of weather systems arriving from the west. Westerly weather increases around the middle of June, bringing wet weather. Anticyclones often dominate the weather in the middle of September, broken by stormy weather in late September, and then more fine anticyclonic weather arrives at the end of September and in early October. FOGS and FROST are likely in the middle of November, caused by more anticyclones. DEPRESSIONS arriving from the west usually make early December a time of mild, wet weather.

Seasonal variations that last rather longer were identified by Hubert Lamb (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). He called them NATURAL SEASONS.

November 3 is Culture Day in Japan and according to tradition the weather is usually fine. Naoki Sato and Masaaki Takahashi, who are scientists at the Center for Climate System Research at the University of Tokyo, have studied weather records for Tokyo over 38 years. They found that the November 3 singularity is real, and there are similar singularities in April and to a lesser degree in October.

Singularities also occur during the Asian summer MONSOON. These are associated with climatological intra-seasonal oscillations, and they produce times when the weather becomes suddenly wetter or drier. For example, the weather is usually dry from August

29 through September 2 in the western North Pacific monsoon region at longitudes 140°E and 15–20°E.

sink An area that forms a receptacle for materials which are moving through a system. For example, some atmospheric CARBON DIOXIDE dissolves in seawater, where it is transported into the deep ocean. The ocean therefore acts as a sink for that carbon dioxide. Soil absorbs CARBON MONOXIDE and also solid particles that are removed from the air by rainout (*see* CLOUD CONDENSATION NUCLEI), snowout (*see* SNOW), and washout (*see* RAINDROPS), so the soil is a sink for these substances. A sink represents the end-point of a transport system that begins with the release of a substance into the environment. The place or process that releases the substance is called its source.

sky-view factor The amount of sky that can be seen from a particular point on the surface, expressed as a proportion of the total sky hemisphere.

smog A form of air pollution that used to occur frequently in winter in many large industrial cities but that was most closely associated with London, where pea soupers were a familiar feature of winter weather. Following the London smog incidents (*see* AIR POLLUTION INCIDENTS), legislation was enacted to prevent the burning of coal in open fires, and with the primary cause of smog removed this type of pollution ceased. Smog of this type is quite different from the PHOTOCHEMICAL SMOG that occurs in cities such as Los Angeles and Athens.

Smog is a contraction of *smoke* and *fog*. An atmospheric scientist named H. A. Des Voeux was the first person to use the term in 1905, but the phenomenon was far from new. It had been increasing in London since at least 1600, most rapidly in the 17th and 19th centuries.

Like many cities, London is low-lying, and a large river flows through its center. EVAPORATION from the river, as well as TRANSPIRATION from plants in the many parks and open spaces, ensures that the air is often moist, and DUST and other particles from the urban environment provide ample CLOUD CONDENSATION NUCLEI (CCN). Temperature INVERSIONS are also fairly common, and in winter, when the air is cool, the relative HUMIDITY beneath an inversion often exceeds 100 percent. WATER VAPOR condenses onto the CCN and the result is a FOG.

Coal and wood burn very inefficiently on domestic open fires. When heated, they emit combustible gases, of which only a proportion ignites to produce the fire. The remainder rises up the chimney. As the gases rise, they also cool and condense into solid particles. This is SMOKE, and in 1952 the domestic fires and coal-burning industrial furnaces of London emitted 157,000 tons (143,000 tonnes) of it. Between August 1944 and December 1946, in the London suburb of Greenwich there were an average of 20 days a month when the VISIBILITY was good at 0900 hours. In the city center there were fewer than 15 such days.

When smoke and fog were trapped together beneath an inversion, smoke particles adhered to and mixed with the water droplets. Sulfate particles, produced from sulfur dioxide emitted from the burning of coal with a high sulfur content, dissolved in the water to produce sulfuric acid (H_2SO_4). This made the smog acid, causing damage to buildings by ACID DEPOSITION. Sulfur dioxide came mainly from the coal burned in power plants and factories, rather than from domestic fires.

Burning coal also released CARBON DIOXIDE and increased the proportion of carbon dioxide to OXYGEN (the CO_2 partial pressure) beneath the inversion. This made some people breathe faster and more deeply, exacerbating the irritation to the respiratory passages caused by the acid smog itself.

Smog made window curtains and washing hanging outdoors filthy and deposited soot particles on the hands, faces, and clothes of people outdoors in it. It was visible as a haze even indoors.

A pea souper was a type of smog in which visibility was reduced to less than 30 feet (10 m)—and sometimes to very much less. The name refers to the yellowish color of the smog, reminiscent of the color of pea soup, when the mixture contained more smoke than fog. Traveling through a pea souper was difficult. Street lights remained lit throughout the day and road vehicles used their lights, but at times drivers were unable to see the edge of the road and became badly disoriented. Pedestrians fared only slightly better. In the thickest smogs it was difficult for them to see the ground beneath their feet. Factories, offices, and schools had to close early because of the long time it would take workers and students to travel home, and sometimes they would remain closed for two or more days, because travel was so difficult. Fortunately, pea soupers no longer occur.

smoke Smoke is an AEROSOL produced by the incomplete combustion of a carbon-based fuel. It consists of solid or liquid particles, most of which are smaller than 0.00004 inch (1 μm) in diameter.

When coal, wood, or some types of oil are heated, certain of their ingredients vaporize. Not all of the vapors ignite. Instead, they are carried up the chimney on the rising current of warm air. When these gases mix with the colder air higher up the chimney or outside, the vapors condense once more. These condensed particles, mixed with fine particles of ash, form soot (*see* AIR POLLUTION). Soot is readily ignited, producing more unburned vapors that also condense as they cool in the outside air. Smoke is the mixture of ash and recondensed volatile ingredients from the original fuel.

Smoke particles contain a large proportion of carbon. This gives them a dark color, because of which they absorb radiation and have a warming effect on the air. Smoke can also increase cloud formation and planetary ALBEDO, however, while at the same time reducing PRECIPITATION. Smoke particles are small enough to be active CLOUD CONDENSATION NUCLEI. WATER VAPOR condenses onto them (and becomes acid, *see* ACID DEPOSITION), but the very small size of the particles produces very small CLOUD DROPLETS. Observations over areas in Central and South America where surface vegetation was being burned during the dry season found that the average size of cloud droplets decreased from 0.0006 inch (14 μm) to 0.0004 inch (9 μm). Small droplets are less likely than large droplets to fall as precipitation. The cloud albedo increased slightly, reducing the amount of sunshine reaching the ground and therefore the surface temperature, but by an insignificant amount.

In colder climates, smoke can mix with FOG to produce SMOG. This has been responsible for many of the most serious incidents of AIR POLLUTION, including the London smog incidents (*see* AIR POLLUTION INCIDENTS).

Black smoke is produced when hydrocarbons are cracked (decomposed by heat) and then cooled suddenly. This releases particles of carbon, which are black.

Brown smoke contains particles of tarlike compounds. It is produced when coal is burned at a low temperature.

The top of a layer of smoke that is trapped beneath an INVERSION and that is seen from above and against the clear sky forms a smoke horizon. The smoke hides both the ground and the true horizon, so the boundary between the smoke and the clear air forms a false horizon.

smudging Using oil-burning heaters, called smudge pots, can protect a delicate farm crop against FROST damage. This is called smudging. In Florida citrus orchards as many as 70 burners are used to every acre (173 per hectare).

The smudge pots are lit on clear, cold nights when frost is likely. They may be used in conjunction with large propellers mounted on tall columns that are used to mix the air and prevent cold air from settling in frost hollows.

Protection can also be achieved by an alternative version of smudging in which materials are burned in order to produce voluminous amounts of black smoke. The smoke forms a layer above the ground, reducing the amount of heat that is lost by infrared radiation from the surface.

snow Snow is PRECIPITATION that falls as aggregations of ICE CRYSTALS. If large, these aggregations form SNOWFLAKES. An irregular crystal is a particle of snow that consists of a number of very small crystals that have formed erratically, so the resulting particle has an irregular shape. Irregular crystals are sometimes covered with a coating of RIME FROST. Snow that has an irregular crystalline structure is called amorphous snow. Snow grains, also called granular snow or graupel, are very small particles of white, opaque ice. The grains are flat and less than 0.04 inch (1 mm) in diameter.

Freshly fallen snow is usually white, but it may be brown. Brown snow is snow that is mixed with dust and by carrying dust or other particles to the ground the falling snow removes them from the air. This process is called snowout. The solid particles act as FREEZING NUCLEI or CLOUD CONDENSATION NUCLEI and the process is identical to rainout, but the precipitation falls as snow, not rain.

Snow formation begins in clouds with the freezing of WATER onto freezing nuclei. The resulting ice crystals continue to grow at the expense of supercooled water droplets (*see* SUPERCOOLING) until they are too heavy to remain airborne and fall from the base of the cloud. Unless the air TEMPERATURE between the CLOUD BASE and the ground is lower than 39°F (4°C), the snow will melt and reach the surface as rain.

Dry snow consists of ice crystals with no liquid water between them. The individual crystals are joined to each other directly or by necks of ice. Dry snow provides good thermal insulation. Small animals survive well beneath it and can move freely through tunnels they excavate. Wet snow includes 3–6 percent of liquid water held inside the crystal aggregations and in crevices between crystals.

The depth of snow that is lying on the ground at a particular time is known as the snow accumulation. Above the permanent SNOW LINE there is a net accumulation of snow. The term *snow cover* describes all the snow that is lying on the ground, or the proportion of an area that lies beneath snow. Ground is usually said to be snow-covered if more than 50 percent of its area lies beneath snow.

Freshly fallen snow that is very light and unstable is called wild snow. Once snow has fallen, the ice crystals begin to pack together under their collective weight and the layer of snow becomes denser. This happens more quickly with wet snow than with dry snow.

Fine, powdery snow that is suddenly thrown upward because of the disturbance caused when a thick layer of underlying snow settles abruptly is known as a snow geyser. Such settling is sometimes called a snow tremor or snowquake.

Snow melts when sunshine raises its surface temperature above freezing, but if the temperature subsequently falls below freezing again, the melted snow will refreeze as a crust of ice across the snow surface. Slush is a mixture of melting snow and/or ice and liquid water that is lying on the ground. It has a soft consistency and is very wet. Slush forms when snow and ice start to thaw, when rain mixes with them, or when they are treated, for example with salt, to lower the melting point (*see* FREEZING).

Blowing snow consists of snow grains that are lifted from the ground by the wind and transported through the air at a height of 6 feet (1.8 m) or more in amounts that are large enough to reduce VISIBILITY significantly. Snow that is lifted, but not to this height, will form snowdrifts, but it will not reduce visibility. Blowing snow can cause a WHITEOUT, and it forms one type of BLIZZARD. A snow banner, also called a snow plume or snow smoke, is the appearance, when seen from a distance, of snow that is being blown from a mountaintop or other exposed high ground. Very fine, powdery snow that is driven by the wind is called snow dust.

Driven snow is snow that has been transported by the wind and deposited in snowdrifts, which are accumulations of snow that is much deeper than the snow covering adjacent areas. A snowdrift that is shaped like a sand dune, having formed in the same way, is called a snow dune. A wind ripple, also called a snow ripple, is a wavelike pattern on the surface of snow that is produced by the wind and forms at right angles to the wind direction.

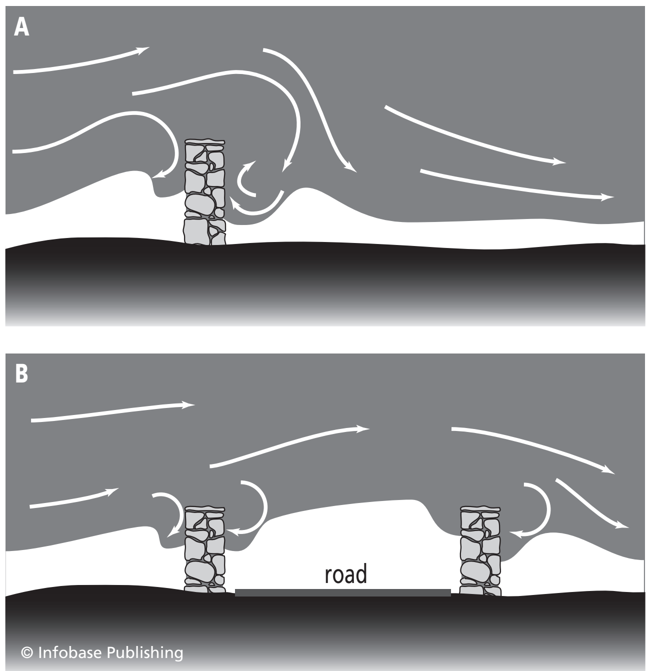
Snowflakes are carried by moving air, and the ability of air to transport them is proportional to its KINETIC ENERGY. If the air loses energy, it also loses its ability to keep snowflakes aloft, so they fall to the ground. Drifts occur where moving air has lost a significant amount of its energy.

Air loses energy by friction with the surface. When it encounters woodland or a belt of trees, moving air slows and some of its snow falls. The snow falls fairly evenly, however, so although the depth of snow is likely to be greater inside the wooded area than it is on open ground on the upwind side, the difference is not large. The overall effect is to collect snow from the passing air and reduce the amount falling on the LEE side. EDDIES will tend to accumulate small drifts on the lee sides of isolated plants.

Solid barriers, such as a wall or high banks on either side of a road, have a much bigger effect. Air approaching below the level of the top of a wall will strike it and be deflected in an eddy. The resulting loss of energy will cause the air to lose snow, but the eddy will also scour snow away from the side of the wall. There will be a space between the thin layer of snow lying against the base of the windward side of the wall and the deep drift. On the lee side, air crossing the top of the wall will eddy downward. This will have a similar scouring effect, and a space will separate the drift from the wall.

A road that is bordered by high banks will fill with snow if the air crosses the road approximately at right angles. The banks have the same effect as a wall, but in this case there are two barriers and the downwind drift caused by one overlaps the upwind drift caused by the other.

A snow fence produces a low drift on its upwind side and a much bigger drift on its downwind side. If the fence is erected to prevent snow from forming drifts on a road, the distance between the fence and the road should be equal to 10 times the height of the fence.



A wall (A) produces two snowdrifts, one on each side, with a space between the wall and the drift. High banks lining a road (B) also produce two drifts. In this case, the downwind drift behind one bank overlaps the upwind drift in front of the other bank, so the road quickly fills with snow.

A snowfield is an extensive, approximately level area that is covered uniformly with fairly smooth snow or ice. Snowfields are found in mountainous areas and high latitudes. A small GLACIER or an accumulation of snow and ice that is too small to be called a glacier is also known as a snowfield. It is snowfields that feed alpine glaciers, and when a glacier retreats it may be because of a reduction in the amount of snow falling over the snowfield feeding it.

The thickness of fallen snow does not provide a direct measure of the amount of precipitation, because snowflakes vary greatly in size, depending on the temperature of the air through which they fall, and their size determines the amount of air that they will trap between them as they accumulate. The colder the air, the smaller are the flakes and the more air they trap. A report of the thickness of a snowfall provides useful information for road users and anyone who needs to be outdoors, but it conveys very little meteorological information. Meteorologists need to know the amount of precipitation that has fallen. Consequently, snowfall amounts are always converted into their rainfall equivalents for meteorological purposes. The table below gives the snowfall equivalent of a standard amount of water at different surface air temperatures.

Suppose that a fall of snow covers the ground to a depth of 2 inches (5 cm) and that the air temperature is 15°F (-9.4°C). At this temperature, the ratio of snow to water is 20:1, which means that 20 inches (or centimeters) of snow are the equivalent of one inch (or cm) of water. Expressed mathematically using inches, this is:

$$20/1 = 2/x$$

where x is the amount of water that is equivalent to 2 inches of snow. Divide the equation by 20 and multiply by x and:

$$x = 2/20 = 0.1$$

At this temperature, therefore, 2 inches (5 cm) of snow are equivalent to 0.1 inch (0.25 cm) of water.

A light snow shower of brief duration is known as a snow flurry. A heavy fall of snow is called a snowstorm, although there is no precise definition of the term. If more than about 4 inches (10 cm) falls, snowplows are likely to be called out to clear roads, so this provides one possible way to define a fall of snow that is severe enough to be called a storm.

The weather conditions required to produce snow are no different from those that produce rain, and much of the precipitation that falls as rain begins as snow in the cloud. The heaviest snowfalls occur when the low-level air temperature is between 25°F and 39°F (-4°C to 4°C). This is warm enough for the air to hold a considerable amount of moisture and cold enough to ensure that precipitation falls as snow rather than rain.

Snow to Water Ratios

Temperature		
°F	**°C**	**Ratio**
35	1.7	7 : 1
29–34	-1.7–1.1	10 : 1
20–28	-6.7–-2.2	15 : 1
10–19	-12.2–-7.2	20 : 1
0–9	-17.8–-12.8	30 : 1
less than 0	less than -17.8	40 : 1

That is why the heaviest snowstorms usually occur near the beginning and end of winter.

It is also possible that snow covering the ground chills the air in contact with it and that this causes air to subside, thereby sustaining low AIR PRESSURE high above the surface. These conditions can produce more snowstorms, so one snowstorm may cause another.

Four mechanisms account for most snowstorms. LAKE-EFFECT snow falls when cold air crosses relatively warm water and then encounters cold ground on the far side. Upslope snowfalls occur when air is cooled by OROGRAPHIC lifting. Snow is also produced at a FRONT when warm air is forced to rise over cold air, and by DEPRESSIONS. A particular snowstorm may result from one of these causes or a combination of two or more of them, but depressions cause more storms than any other cause.

In North America, lake-effect snow affects cities to the east of the Great Lakes and also Salt Lake City, to the east of the Great Salt Lake. Salt Lake City is a ski resort that receives abundant snow. One storm on October 18, 1984, delivered 27.2 inches (69 cm) and on February 2, 1989, the city received 20.9 inches (53 cm).

Upslope snow is especially common on the western side of the Rocky Mountains. In the month of January 1911, 390 inches (991 cm) of snow fell on Tamarack, California, and in the winter of 1998–99 Mount Baker, Washington, received 1,140 inches (28.96 meters).

snowball Earth Snowball Earth describes the Earth at times when, apart from the highest mountains, its entire surface is covered by ice. The term was coined in 1992 by the American geobiologist Joseph Kirschvink of the California Institute of Technology. This condition is believed to have occurred four times between 750 million and 580 million years ago. Two of the episodes have been identified. The Sturtian occurred about 710 million years ago and the Marinoan about 635 million years ago. Both ended abruptly, with the continental ICE SHEETS melting completely within about 2,000 years.

Mean temperatures during these glacial episodes were about -58°F (-50°C), and all of the oceans were frozen to a depth of more than 0.6 mile (1 km). Heat from the crust and core of the Earth prevented the oceans from freezing completely.

Dry land then comprised a number of small continents that were formed when a single large landmass broke apart. The interiors of these small continents were closer to the sea than they had been when the continents were joined together, and rainfall over land increased. This washed CARBON DIOXIDE from the air. The carbon dioxide reacted with minerals in the rocks and was carried to the sea, so the atmosphere came to contain less carbon dioxide. Temperatures fell and large ice packs formed in high latitudes. These increased the planetary ALBEDO causing temperatures to fall further (*see* SNOWBLITZ).

Once the oceans were completely sealed, no liquid water was exposed to the air, so EVAPORATION and PRECIPITATION ceased. VOLCANOES continued to erupt, however, releasing carbon dioxide into the air. With no precipitation to remove it, the carbon dioxide accumulated. After about 10 million years, its concentration was high enough to trigger a huge GREENHOUSE EFFECT. The ice melted in a matter of a few centuries, but this did not end the greenhouse warming. Surface air temperatures eventually rose to more than 120°F (50°C). More water evaporated and rainfall became intense. The rain washed carbon dioxide from the air and gradually the climate stabilized.

Further Reading

Allen, Philip A., and Paul F. Hoffman. "Extreme winds and waves in the aftermath of a Neoproterozoic glaciation." *Nature,* 433, 123–127, January 13, 2005.

Hoffman, Paul F. and Daniel P. Schrag. "Snowball Earth." *Scientific American,* January 2000.

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snowblitz The snowblitz theory, popular in the 1970s, proposed that the Northern Hemisphere could be plunged into a full-scale GLACIAL PERIOD in a matter of a few decades. This is what is believed to have happened at the onset of the YOUNGER DRYAS and the proposed mechanism is the same.

The first stage requires a large release of freshwater into the northern part of the North Atlantic. Melting of the whole of the GREENLAND ICE SHEET might release sufficient water, but this is extremely unlikely, and there is no other large ice sheet in the Northern Hemisphere. The only source for the freshwater would therefore be greatly increased PRECIPITATION, perhaps as a consequence of a general rise in temperature.

The second stage involves shutting down the Great Conveyor. Freshwater, from the increased precipitation, is less dense than salt water and would float above it. At first, wave action would mix the two, but as more and more freshwater was added, mixing would become less effective until a layer of freshwater lay permanently above the salt water. The sinking of dense surface water drives the thermohaline circulation, but if the surface water is less dense it cannot sink. This would shut down the Great Conveyor.

With the conveyor shut down, conditions would be set for the third stage in the process. Warm water would no longer flow northward, and the surface of the northern North Atlantic would cool rapidly by releasing its stored heat in the form of infrared radiation. In winter, it would freeze, partly because it would be colder than in previous years and partly because freshwater freezes at a higher temperature than salt water. The area of sea ice would expand, increasing the albedo. This would cause further cooling.

The final stage could then follow. Polar continental air masses that form over North America are very cold in winter. Ordinarily, they warm as they cross the unfrozen Atlantic, but with the Atlantic frozen they would remain cold and would reach Europe essentially unaltered. In summer, when the sea ice melted, the ocean would still be cold, because the North Atlantic Drift (*see* Appendix VI: Ocean Currents) would have disappeared. Consequently, air would be cold and moist when it reached Europe, bringing reduced precipitation (because of reduced water-holding capacity due to the lower air temperature) but an increase in the proportion of precipitation falling as snow. In winter, increased albedo over both land and sea would bring very low temperatures to Europe. The general movement of air from west to east would spread this cooling to the whole of the Northern Hemisphere.

A year would come when not all the snow that fell on land during the winter melted in summer. The high winter albedo would continue through summer, so the temperature would remain low. More snow would accumulate the following winter and the snow-covered area would increase year by year. Temperatures would stabilize at below freezing, and as more snow accumulated its weight would compress the lower layers into glacial ice. Ice sheets would form in Europe and Canada, and each year their edges would advance farther south until a substantial part of both continents was in the grip of an ice age.

According to the snowblitz theory, the entire process, from the rise in temperature and increased rainfall to the formation and rapid advance of the ice sheets, might take no more than a few decades.

Few climate scientists now believe this scenario is credible. Climate models have estimated the consequences of a failure of the thermohaline circulation and the Great Conveyor, and have found that the resulting decrease in temperature is much less dramatic than the snowblitz theory suggests.

snow chill The effect of being covered in snow that then melts. In a blizzard or snowstorm, snow itself affords protection from the wind, and it is possible to survive by digging an ice cave and sheltering inside it. If the snow in contact with a person's clothing begins to melt, however, the latent heat required to melt the snow is taken from the body, reducing its temperature. At the same time melted snow soaks the clothing, filling all the air spaces between the fibers. This water is close to freezing temperature, and water conducts heat much more efficiently than does air. The combined effects of using body warmth to melt snow and then of wearing clothes soaked in very cold water rapidly reduce the core body temperature.

snowflake A snowflake is an aggregation of ice crystals that are grouped into a regular six-sided or six-pointed shape between about 0.04 inch and 0.8 inch (1–20 mm) across. Although all snowflakes have this basic hexagonal form, an extremely large number of variations is possible within it, and consequently every snowflake is unique.

Ice crystals form in clouds where the temperature is below freezing, and once they begin to form they grow at the expense of supercooled water droplets (*see* supercooling). Crystals also fragment as protrusions extending from them are carried away by air currents, so the cloud soon contains splinters of ice that act as freezing nuclei for the formation of new crystals.

The individual crystals are composed of hexagonal units that are arranged in a number of possible shapes. The shapes depend on the temperature at which the crystals form. As they continue to grow beyond their unit shapes, they often do so by accumulating projecting arms or spikes. When crystals collide, their irregular shapes make it likely that they will lock together. The haphazard way this happens explains why no two snowflakes are identical. Snowflakes grow most readily when the temperature is about 32–23°F (between 0°C and -5°C). This is because at just below freezing a thin film of liquid water forms on the surface of each crystal and freezes solid where two crystals make contact.

Tens of individual crystals form a single snowflake, and the flake will continue to grow until its fall speed exceeds the speed of the air currents that carry it upward inside the cloud. Then it falls from the cloud. If it falls through air that is above freezing temperature, it will start to melt and if it remains in air at this temperature for long enough, it will reach the surface as rain rather than snow. It is unlikely to reach the surface as snow if the freezing level is higher than about 1,000 feet (330 m) and the surface air temperature is above 39°F (4°C). Rain is often melted snow and, as Wilson Bentley (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) discovered, the size of RAINDROPS indicates the size of the snowflakes that melted to form them.

Bentley was the most famous student of snowflakes, but he was not the first. In a text called *Moral Discourses Illustrating the Han Text of the "Book of Songs,"* written between 140 and 131 B.C.E., Han Ying described the hexagonal shape of ice crystals and snowflakes. This is the earliest written reference to snowflakes, and their intricate patterns have continued to intrigue scientists ever since. In the 16th century Olaus Magnus (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) referred to them, and in 1611 Johannes Kepler (1571–1630), the German physicist and astronomer, also described them, in a book called *A New Year's Gift, or On the Six-cornered Snowflake*. Robert Hooke (1635–1703, *see* APPENDIX I: BIOGRAPHICAL ENTRIES), the English physicist and one of the first microscopists, studied snowflakes under the microscope and drew what he saw. He published his drawings and descriptions in 1665, in a book called *Micrographia.* In 1936, Professor Ukichiro Nakaya, a Japanese physicist, was the first person to grow ice crystals in a laboratory, and in 1941 this led to the establishment of the Institute of Low Temperature Science at the University of Hokkaido. Professor Nakaya became a leading authority on snow. His book on the subject, called *Snow Crystals: Natural and Artificial,* was published in 1954 by Harvard University Press.

snow gauge A snow gauge is an instrument used to measure the amount of snow that has fallen over a stated period. It is a modified RAIN GAUGE.

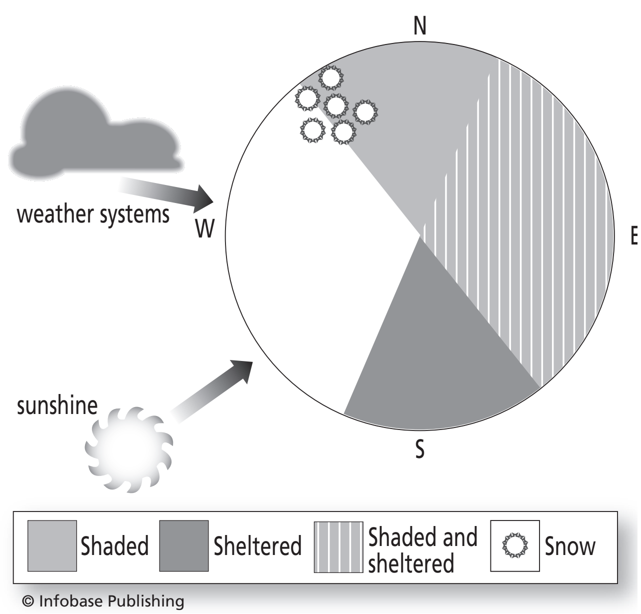
In some snow gauge designs, the top edge of the collecting funnel is heated, so that snow falling on it melts and is collected as liquid water. This automatically converts the snowfall amount into its rainfall equivalent. An alternative design has a removable funnel and receiver, so that snow is collected and measured directly. Snowfall can also be measured by taking a core, using an open-ended cylinder pressed vertically all the way through the snow. The snow is then transferred to a measuring beaker. The beaker is calibrated to correct for any difference between its diameter and that of the coring cylinder. Transferring the snow to the beaker inevitably packs the grains together, so it must be melted and the depth read as the water equivalent. The simplest way to measure snowfall is to use a measuring stick, such as an ordinary ruler, and a THERMOMETER. The ruler will measure the thickness of snow, and the air temperature at the time it fell will indicate the water equivalent. Regardless of the method used, snowfall should always be measured in the open, well clear of trees and buildings that might deflect wind and alter the amount of snow reaching the ground.

The depth of a layer of snow after this has been converted to an equivalent fall of rain is called the water equivalent. Snow traps small pockets of air between its grains and flakes. This makes snow bulky, but to an extent that varies according to the type of snow. When snow is expected, weather forecasts predict the depth of fall people can expect. This is valuable information, but it cannot be used to compare the snowfall in different places and at different times. For comparisons, the depth of snow must be converted into an equivalent depth of water. This is done by pressing an open-ended cylinder vertically through the layer of snow, sliding a plate beneath the lower end to seal it, then removing the cylinder and melting the snow. The depth of liquid water is then recorded as the amount of PRECIPITATION. Liquid water cannot be compressed, so it provides a standard measure. As an approximate guide, the water equivalent is one-tenth the depth of snow. *See* SNOW for the table on converting snowfall to its water equivalent.

snow line The snow line is the boundary between the area covered by snow, for example on a mountainside, and the area that is free from snow. The edge of the snow that remains on a mountainside through the summer is also known as the snow line.

The location of the snow line depends on the TEMPERATURE, which in turn varies with latitude and with elevation. The location of the snow line on a particular mountain can be determined only by measurement, however. It is extremely difficult to calculate, because every mountain has crags shading the area behind them and deep gullies. These are places where snow lingers. The side of the mountain that faces the noonday Sun will be warmer than the side shaded from it and PRECIPITATION will be heavier on the side facing into the direction from which most weather systems arrive. These factors allow an imaginary mountain, which is perfectly conical and smooth, to be divided into four unequal sectors according to whether they are exposed to sunshine, shaded, sheltered from the weather, or both shaded and sheltered. It is possible then to estimate where snow is most likely to fall. The average snow line elevation at various latitudes is given in the table (top, right).

The climatic snow line is the altitude above which snow will accumulate over a long period on a level surface that is fully exposed to sunshine, wind, and precipitation. Below this altitude, ABLATION between snowfalls will be sufficient to prevent snow from accumulating.



The direction of the noonday Sun and the direction from which most weather systems arrive make it possible to divide an idealized mountain into four sectors. The sectors that are sheltered and both shaded and sheltered receive little precipitation, because of the rain shadow effect. Snow is most likely to fall in the sector that is shaded from the Sun but exposed to the weather.

Mean Snow Line

Latitude	Northern Hemisphere (feet)	Northern Hemisphere (meters)	Southern Hemisphere (feet)	Southern Hemisphere (meters)
0–10	15,500	4,727	17,400	5,310
10–20	15,500	4,727	18,400	5,610
20–30	17,400	5,310	16,800	5,125
30–40	14,100	4,300	9,900	3,020
40–50	9,900	3,020	4,900	1,495
50–60	6,600	2,010	2,600	793
60–70	3,300	1,007	0	0
70–80	1,650	503	0	0

soil air Soil air is the air held in the spaces between soil particles. In the upper layer of a cultivated soil, air accounts for about 25 percent of the volume. Soil air is similar in composition to atmospheric air and most of the constituents are present in similar proportions. The exception is CARBON DIOXIDE (CO_2). Atmospheric air contains about 0.04 percent CO_2, but soil air contains about 0.65 percent. The CO_2 in the soil comes from RESPIRATION by plant roots and soil organisms, including those engaged in decomposing organic matter. In some soils the proportion of OXYGEN decreases with increasing depth, and that of CO_2 increases by a similar amount. Some of the soil CO_2 dissolves in water and is removed as carbonic acid ($H_2O + CO_2 \rightarrow H_2CO_3$).

soil classification Soil classification is any method for labeling different types of soil to distinguish their characteristics. Modern classifications are based on principles similar to those used to classify living organisms and clouds (*see* CLOUD CLASSIFICATION).

The earliest attempts to classify soils were made in classical times, but the first steps toward the modern system were made in the latter part of the 19th century by Russian scientists led by Vasily Vasilievich Dokuchaev (1840–1903). Dokuchaev based his classification on the climates in which soils form. His classification was widely adopted, and many of the original Russian names for soil types are still used, although now some of them are used only informally and others have been redefined, because the old system has been replaced. Soil names such as podzol, chernozem, and rendzina are taken from the early Russian work. Podzols are gray, ashlike, acid soils. Chernozems are black grassland soils sometimes called prairie soils, and rendzinas are brown soils found in humid or semi-arid grasslands.

American soil scientists were also working on the problem, and by the 1940s their work was more advanced than that of their Russian colleagues. By 1975, scientists at the Soil Survey of the United States Department of Agriculture had devised a classification they called Soil Taxonomy. It divides soils into 12 main groups, called orders. The orders are divided into 47 suborders, and the suborders are divided into groups, subgroups, families, and soil series, with six phases in each series. The classification is based on the physical and chemical properties of the various levels, or horizons, that make up a vertical cross section, or profile, through a soil. These were called diagnostic horizons. Some of the names seem strange on first acquaintance, and they become still stranger at levels below that of the order. The suborders include Psamments, Boralfs, and Usterts, the great groups include Haplargids, Haplorthods, and Pellusterts, and the subgroups include Aquic Paleudults, Typic Medisaprists, and Typic Torrox.

The 12 orders are listed below, with a brief description of each.

Gelisols are soils where there is PERMAFROST within 6.5 feet (2 m) of the surface.

Histosols are soils rich in organic matter that are found in bogs and marshes, where the climate is cool and wet.

Spodosols are sandy, strongly acid soils that are found in forests, especially coniferous forests.

Andisols are soils that form from volcanic ash; they are deep and light-textured.

Oxisols are deeply weathered (*see* WEATHERING), acid soils from which most of the plant nutrients have been washed away; they are found in the humid TROPICS and subtropics.

Vertisols are clay soils that swell when they are wet and develop deep cracks when they are dry; they are found in climates with marked wet and dry seasons.

Aridisols are desert soils that contain little organic matter; they often have salt layers.

Ultisols are strongly acid, deeply weathered, tropical soils.

Mollisols are very dark, grassland soils that are rich in organic matter and highly fertile.

Alfisols are soils found mainly in forests where the annual rainfall is 20–50 inches (510–1,270 mm); there is a layer of clay beneath the topsoil.

Inceptisols are soils found in cold, wet climates; they are at an early stage in their development.

Entisols are soils with little vertical development into layers; they are found on recent floodplains, beneath recently fallen volcanic ash, and as wind-blown sand.

National classifications, such as the Soil Taxonomy, are often very effective in describing the soils within their boundaries, but there was a need for an international classification. In 1961, representatives from the Food and Agriculture Organization (FAO) of the United Nations, the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the International Society of Soil Science (ISS) met to discuss preparing one. The project was completed in 1974. Like the Soil Taxonomy, it was based on diagnostic horizons. It divided soils into 26 major groups, subdivided into 106 soil units. The classification was updated in 1988 and has been amended several times since. It now comprises 30 reference soil groups and 170 possible subunits.

The FAO reference soil groups are listed below.

Histosols are soils with a peat layer more than 15.75 inches (40 cm) deep.

Cryosols are soils with a permanently frozen layer within 39 inches (100 cm) of the surface.

Anthrosols are soils that have been strongly affected by human activity.

Leptosols are soils with hard rock within 10 inches (25 cm) of the surface, or with more than 40 percent calcium carbonate ($CaCO_3$) within 10 inches (25 cm) of the surface, or less than 10 percent of fine earth to a depth of 30 inches (75 cm) or more.

Vertisols are soils with a layer more than 20 inches (50 cm) deep containing more than 30 percent clay within 39 inches (100 cm) of the surface.

Fluvisols are soils formed on river (alluvial) deposits with volcanic deposits within 10 inches (25 cm) of the surface and extending to a depth of more than 20 inches (50 cm).

Solonchaks are soils with a salt-rich layer more than 6 inches (15 cm) thick at or just below the surface.

Gleysols are soils with a sticky, bluish-gray layer (gley) within 20 inches (50 cm) of the surface.

Andosols are volcanic soils having a layer more than 12 inches (30 cm) deep containing more than 10 percent volcanic glass or other volcanic material, or weathered volcanic material within 10 inches (25 cm) of the surface.

Podzols are pale soils with a layer containing organic material and/or iron and aluminum that have washed down from above.

Plinthosols are soils with a layer more than 6 inches (15 cm) deep containing more than 25 percent iron and aluminum sesquioxides (oxides comprising two parts of the metal to three of oxygen) within 20 inches (50 cm) of the surface that hardens when exposed.

Ferralsols are soils with a subsurface layer more than 6 inches (15 cm) deep with red mottling due to iron and aluminum.

Solonetz are soils with a sodium- and clay-rich subsurface layer more than 3 inches (7.5 cm) deep.

Planosols are soils that have had stagnant water within 40 inches (100 cm) of the surface for prolonged periods.

Chernozems are soils with a dark-colored, well-structured, basic surface layer at least 8 inches (20 cm) deep.

Kastanozems are soils resembling chernozems, but with concentrations of calcium compounds within 40 inches (100 cm) of the surface.

Phaeozems include all other soils with a dark-colored, well-structured, basic surface layer.

Gypsisols are soils with a layer rich in gypsum (calcium sulfate, $CaSO_4.2H_20$) within 40 inches (100 cm) of the surface, or more than 15 percent gypsum in a layer more than 40 inches (100 cm) deep.

Durisols are soils with a layer of cemented silica (silicon dioxide, SiO_2) within 40 inches (100 cm) of the surface.

Calcisols are soils with concentrations of calcium carbonate within 50 inches (125 cm) of the surface.

Albeluvisols are soils with an irregular upper surface and a subsurface layer rich in clay.

Alisols are slightly acid soils containing high concentrations of aluminum and with a clay-rich layer within 40 inches (100 cm) of the surface.

Nitisols are soils with a layer containing more than 30 percent clay more than 12 inches (30 cm) deep and no evidence of clay particles moving to lower levels within 40 inches (100 cm) of the surface.

Acrisols are acid soils with a clay-rich subsurface layer.

Luvisols are soils with a clay-rich subsurface layer containing clay particles that have moved down from above.

Lixisols comprise all other soils with a clay-rich layer within 40–80 inches (100–200 cm) of the surface.

Umbrisols are soils with a thick, dark-colored, acid surface layer.

Cambisols are soils with an altered surface layer or one that is thick and dark-colored, above a subsoil that is acid in the upper 40 inches (100 cm) and with a clay-rich or volcanic layer beginning 10–40 inches (25–100 cm) below the surface.

Arenosols are weakly developed soils with a coarse texture.

Regosols are all other soils.

An acid soil is one with a pH of less than 7.0. A basic soil is one with a pH greater than 7.0.

Further Reading

Ashman, M. R., and G. Puri. *Essential Soil Science.* Oxford: Blackwell Science Ltd., 2002.

soil moisture WATER that is present in the soil. Since all living organisms require water, the amount of soil moisture affects the rate of biological activity in the soil, including the rate at which organic matter decomposes.

Many organisms also require OXYGEN for RESPIRATION, and they obtain it from air that is trapped in spaces between soil particles. If the soil is completely saturated, these spaces are filled with water and the air is expelled, so too much water is as bad as too little. For most soil organisms, the optimum amount of soil moisture is 50–70 percent of field capacity.

Field capacity is the amount of water that a particular soil will retain under conditions that allow water to drain freely from it. It is measured by thoroughly soaking a measured weight of oven-dried soil, then leaving it to drain for a day or two before weighing it again. Field capacity is usually reported as a percentage of the oven-dried weight of the soil.

When water arrives at the soil surface, by falling as PRECIPITATION or flowing from adjacent land, it drains downward under the force of gravity. The antecedent precipitation index is a summary of the amount of precipitation that falls each day in a particular area, weighted so it can be used to estimate soil moisture. The speed with which water moves depends on the PERMEABILITY of the soil, but even when most of the water has drained away to join the GROUNDWATER, a film of water up to 15–20 molecules thick remains, covering all the soil particles.

The amount of water held in a soil is measured by weighing a sample of soil before and after drying it in an oven at 221°F (105°C) or by using an instrument such as a neutron probe to measure the electrical conductivity of the soil between two electrodes. The neutron probe is lowered into a pipe, about 2 inches (5 cm) in diameter and of an appropriate length for the conditions being studied. Electrodes are suspended in the pipe at the levels being monitored. The probe contains a radioactive source that emits fast (high-energy) neutrons. When the neutrons collide with HYDROGEN atoms, they change direction and slow down and some of the slow neutrons are deflected back into the probe, where they are counted. The greater the number of slow neutrons the probe detects, the greater is the water content of the soil, because water molecules are the major source of hydrogen atoms.

As water moves through the soil, the hydrogen atoms in its molecules, which carry positive charge, are attracted to oxygen atoms, bearing negative charge, at the surface of molecules of mineral particles. The water molecules attach themselves quite firmly to the mineral particles. This force is called adhesion.

Water molecules are also attached to one another by hydrogen bonds (*see* CHEMICAL BONDS). This force is called cohesion, and because of it other water molecules attach themselves to the molecules coating exposed mineral particles. The resulting film of water is held together by both adhesion and cohesion.

In addition, soil particles absorb moisture from the atmosphere. This is called hygroscopic moisture. It is held very tightly by the particles and cannot enter the root hairs of plants.

Adhesive and cohesive forces act on surfaces—of mineral particles and water, respectively. Consequently, the amount of water a soil can retain in this way depends on the amount of surface area its particles present. The bigger the soil particles, the smaller their total surface area is.

Soil particles are not spherical, of course, but the ratio of their radius to surface area obeys the same geometrical law. The surface area of a sphere is equal to $4\ \pi r^2$, where r is the radius. If $r = 2$, then the surface area is 50. If $r = 4$, then the surface area is 201. The volume of each of these particles ($4/3\ \pi r^3$) is 33.5 and 268, respectively, so any volume of soil will contain many more of the smaller particles than of the bigger ones. For example, a soil volume of 10,000 will contain 298 of the small particles, but only 37 of the big ones, and the total particle surface area will be 14,900 in the soil with small particles and about 7,440 in the other soil. That is why SAND, with big particles, holds much less water than silt or clay, with very small particles.

Considerable force is needed to remove the film of water from soil particles. Adhesion water moves very little, but cohesion water is more mobile. Adhesion water is not available to plants, but molecules of cohesion water are constantly joining and leaving the water flowing through the soil. Water flowing downward through the soil is called gravitational water. It is held in the soil with a force that is less than about 30 kPa (300 mb, 4.5 lb/in^2). Water that can be absorbed by plant roots is called available water, and it is held with a force of about 30–1,500 kPa (0.3–15 bar, 4.5–218 lb/in^2). Adhesion water is held with a force equal to 1.5–100 MPa (15–1,000 bar, 218–14,500 lb/in^2).

Water that has drained to below the water table may then move upward again by CAPILLARITY.

Where the amount of water supplied by precipitation and available to plants (usually crop plants) is smaller than the amount needed to sustain healthy plant growth, the difference is called the water deficit. The water surplus is the difference between the amount of water that is needed to sustain the healthy growth of plants (usually crop plants) and the amount supplied by precipitation that is available to plants, where the amount available is greater than the amount required.

solar constant The solar constant is the amount of energy that the Earth receives from the Sun per unit area (usually per square meter) calculated at a point perpendicular to the Sun's rays and located at the outermost edge of the Earth's atmosphere. The value of the solar constant is not known precisely, but the best estimate is 127 watts per square foot (1,367 watts per square meter, 1.98 langleys, *see* UNITS OF MEASUREMENT).

The Sun generates energy by means of thermonuclear reactions in its core. The Sun is made from gas, about 75 percent HYDROGEN and 25 percent HELIUM, and its mass is 743 times that of the combined masses of all the planets in the solar system. It is 330,000 times more massive than Earth. This mass exerts a gravitational force on the Sun itself, pressing material inward. The inward gravitational pressure is so great at the core that the electrons are stripped away from atomic nuclei. These are predominantly hydrogen nuclei, each of which consists of a single proton.

Protons carry positive charge and repel one another, but the pressure at the solar core is sufficient to overcome this repulsion and to force protons together. This causes a reaction known as the proton–proton cycle in which four hydrogen nuclei combine to make one helium nucleus.

Later stages in the series of reactions that comprise the proton–proton cycle can follow several different paths, but they all begin with the combination of two hydrogen nuclei to make one deuterium (heavy hydrogen) nucleus with the release of a positron (positive electron, e^+) and a neutrino (ν).

$$^1H + ^1H \rightarrow ^2H + e^+ + \nu$$

The deuterium nucleus then captures a third proton. This produces a nucleus of helium-3 (^3He) with the release of a gamma ray (γ).

$$^2H + ^1H \rightarrow ^3He + \gamma$$

The final result of the cycle is the production of helium-4 (^4He) with the loss of 0.7 percent of the original mass of the protons. The lost mass is converted into energy according to the Einstein equation $E = mc^2$, where E is energy, m is mass, and c is the speed of light. A little of the energy is carried away by neutrinos, but most is converted into heat.

The TEMPERATURE inside the solar core is about 27 million degrees F (15×10^6 K = 15×10^6°C). The heat makes the material in the core expand, so it exerts an outward pressure. The outward pressure of expansion precisely balances the inward, gravitational pressure, so the Sun neither expands nor collapses.

The core heats the outer layers of the Sun. The outermost visible layer is called the photosphere. Its temperature is approximately 10,960°F (5,800 K = 6,073°C). Although the temperature is higher in the chromosphere and solar corona, neither of which is visible except during a solar ECLIPSE, these consist of matter that is so tenuous it has little effect on the emission of energy from the Sun. The effective temperature of the Sun is 10,960°F (5,800 K). The chromosphere and corona lie beyond the photosphere. The corona is the source of the SOLAR WIND.

The total amount of energy radiated by the Sun is given by the STEFAN–BOLTZMANN LAW. Earth receives only a small proportion of this energy, about 4.5×10^{-10} of the total. The radius of the Sun (R) is 109 times that of the Earth, but its average distance from the Earth, of 93 million miles (149.5 million km), is equal to 215R and it subtends an angle of only 0.5° in the sky. The amount of solar energy intercepted by Earth, the solar constant (S), is equal to $S_O/4\pi R_E^2$, where S_O is the solar output and R_E is the radius of the Earth. It is this calculation that yields the value of 127 watts per square foot (1,367 W/m^2). Although called a constant, the solar constant varies with changes in the solar output.

Clouds and the surface reflect a proportion of the solar radiation reaching the top of the atmosphere. This proportion represents the planetary ALBEDO (a) and it must be deducted from the solar constant ($S - a$) to give a value for the amount of solar energy reaching the surface.

Irradiance is the rate at which radiant solar energy flows through a unit area that is perpendicular to the radiation beam. Since the Sun emits radiation equally in all directions, illuminating a sphere around itself, irradiance decreases with distance from the Sun in accordance with the INVERSE SQUARE LAW. The irradiance at any point (I) is given by the equation: $I = I_s(R_s/R)^2$, where I_s is the amount of radiation being emitted by the Sun, R_s is the radius of the photosphere, and R is the distance of the point from the Sun.

solar energy Solar energy is energy that the Earth receives from the Sun and that can be used to perform useful tasks, such as providing space and water heating and generating electrical power. Although the concept of solar energy is sometimes extended to include WIND POWER, because wind is produced by weather systems driven by solar energy, the term strictly covers only the direct use of solar radiation in the form of heat or light.

Sometimes the generation of energy by burning biomass is also included. This is the growing of crops, such as fast-growing trees, that can be harvested for fuel, or that produce large amounts of sugar, such as corn (maize) and sugar beet, that can be fermented to produce alcohol (ethanol) for use as a liquid fuel. These technologies are included because the crops grow by means of PHOTOSYNTHESIS, which is powered by sunlight.

In principle, a huge amount of energy is available. The surface of the Earth receives about 9.5×10^{17} calories (4×10^{18} J) of energy a year, while the total annual energy consumption of the entire human population of the Earth amounts to only about 7.2×10^{13} cal (3×10^{14} J).

The simplest direct use of solar heat is also the most traditional: south-facing (in the Northern Hemisphere) windows. Add double-glazing to reduce heat loss, and the window allows solar energy to enter the building and warm its interior and contents, but prevents warm air and long-wave BLACKBODY radiation from leaving (*see* GREENHOUSE EFFECT).

A flat-plate solar collector heats water. It consists of a large, shallow box covered with glass and with a base that is painted matt black to absorb radiation. The box contains piping that winds back and forth across the base. Water is either pumped or flows by gravity through the piping. Solar radiation passes through the glass plate, is absorbed by the black base, and heat passes by conduction from the black base to the pipes and the water they contain. The piping carries the heated water inside the building to a heat exchanger in a water tank. Usually a number of solar collectors are mounted as an array on the roof and angled to face the noonday Sun.

Solar collectors are effective provided they are sited in a place where they receive an adequate amount of solar radiation. They are especially useful in latitudes between about 36°N and 36°S. Their disadvantage is that they require warm sunshine. That means they work best during daytime in summer and are much less useful at night, in winter, and when the sky is overcast, which are the time when heat is most needed. They must also be cleaned frequently, because dirt on the exterior glass shades the interior of the box.

Mirrors can be used to focus solar radiation onto a central point. Several devices, called solar furnaces, have been built to exploit this, and these produce temperatures high enough to heat water to drive generating turbines. Several of solar furnaces are located in the United States, the largest being at Albuquerque, New Mexico.

Solar cells, which are also known as photovoltaic cells, produce an electric current directly by the action of sunlight. When light strikes certain semiconductor materials, some of the light energy frees electrons in the material. An electric field in the material forces all the free electrons to move in the same direction. This constitutes an electric current. Solar cells were developed primarily for use in space, and they supply much of the energy for spacecraft and orbiting satellites. They are also starting to be installed for energy production on the surface. In sunny locations that are too remote to be reached by conventional power lines, solar cells may be less costly than alternative forms of generation.

A solar pond exploits the difference in DENSITY between freshwater and salt water. Typically, a pond several feet deep and with a large surface area is lined with black plastic to absorb radiant heat. A layer of water saturated with salt covers the lower part of the pond and a layer of freshwater is poured on top of it, taking care that the two layers do not mix. Freshwater then floats above the denser salt water. Sunshine heats the black plastic, which warms the salt water in contact with it. CONVECTION currents distribute the absorbed heat throughout the salt water layer, but without affecting the overlying freshwater layer. When the salt water reaches a satisfactory temperature—close to 212°F (100°C)—it is piped away to a heat exchanger, where the hot water heats a tank of freshwater. The salt water then passes back into the pond. The freshwater layer must be replenished from time to time to compensate for EVAPORATION, but covering the pond with clear plastic minimizes evaporation losses.

Further Reading

Allaby, Michael. *Deserts*. Rev. ed. Ecosystem. New York: Facts On File, 2007.

solar irradiance Solar irradiance is the total amount of energy that the Sun emits. The STEFAN-BOLTZMANN LAW relates this to the TEMPERATURE at the surface of the photosphere, which averages about 10,960°F (5,800K). At this temperature the total amount of energy radiated by the Sun (its EXITANCE) is about 70 MW/m^2, and over the entire surface of the photosphere it is about 4.2×10^{20} MW. Emitting energy at this rate, the Sun has so far converted about 0.1 percent of its mass into energy (*see* SOLAR CONSTANT). The temperature of the photosphere varies slightly, however, and therefore so does the amount of energy it radiates. In 1977, for example, the Kitt Peak National Observatory near Tucson, Arizona, measured a drop of 19.8°F (11K) in the temperature of the photosphere in a single year. This is very small (a drop of about 0.18 percent), but if it were sustained for a decade or more it would produce a slight but noticeable cooling of the Earth's climate.

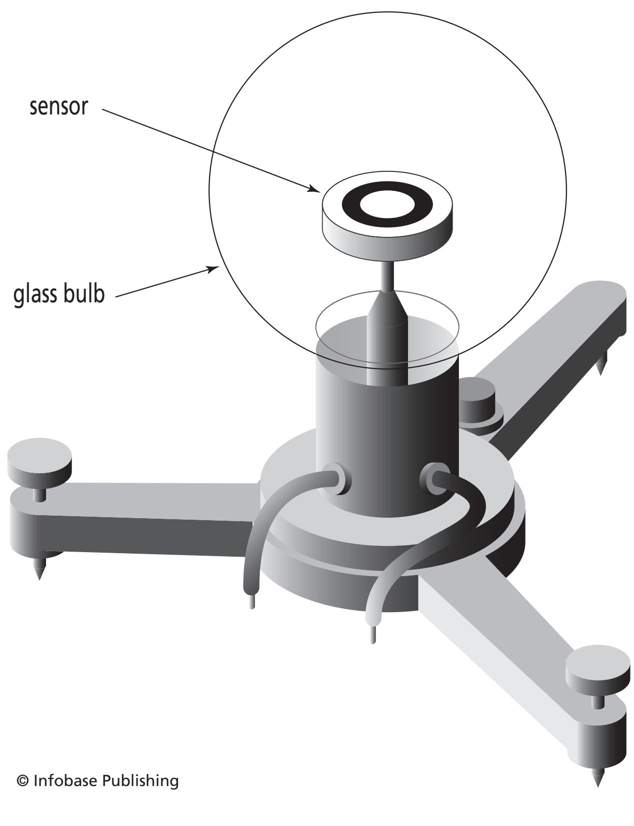
During the 1990s, the solar output increased, peaking in 2000. The amount of cloud over the surface of the Earth, and especially of low cloud, is directly proportional to the intensity of COSMIC RADIATION reaching the atmosphere. Cosmic radiation consists of charged particles. When the charged particles enter the atmosphere, they ionize (*see* ION) AEROSOL particles, which then clump together to form CLOUD CONDENSATION NUCLEI. The charged particles are also deflected by the SOLAR WIND. Consequently, the intensity of cosmic radiation decreases at times of increased solar output and a stronger solar wind. This reduces cloud formation, and with fewer clouds the planetary ALBEDO decreases. More solar energy is then absorbed by the surface and the global climate grows very slightly warmer. Some scientists believe that the increased solar output during the 1990s is a significant cause of the slight increase in global temperatures that were recorded and that the effect of changing solar output on the intensity of cosmic radiation and cloud formation is the mechanism by which this occurred. Records since solar output peaked in 2000 have shown no change in the rate of GLOBAL WARMING, however, although this could be due to the time taken by the atmosphere to respond.

The amount of electromagnetic radiation emanating from a body such as the Sun or falling on a surface is called the radiant flux density. It is measured in watts per square meter (W/m^2), langleys (*see* UNITS OF MEASUREMENT), or calories per square centimeter (cal/cm^2). The total OPTICAL AIR MASS of the atmosphere that is penetrated by light from the Sun with the Sun at any given position in the sky is known as the solar air mass.

Transmissivity is a measure of the transparency of the atmosphere to incoming solar radiation. It is the fraction of the solar radiation incident on the top of the atmosphere that reaches the surface in a direct beam (not as diffuse radiation). Transmissivity varies with the state of the atmosphere—HAZE and AIR POLLUTION reduce it—and by the distance the radiation must travel through the atmosphere, or the PATH LENGTH. Zenith transmissivity is a measure of the fraction of solar radiation reaching the top of the atmosphere when the Sun is directly overhead (at zenith) that penetrates to the surface. The term is used to describe the transparency of the atmosphere and is calculated in relation to the zenith even for places outside the TROPICS, where the Sun is never directly overhead.

Several instruments are used to measure solar irradiance. A diffusograph measures diffuse radiation from the sky. It consists of a pyranometer surrounded by a circular strip set at such an angle that as the Sun crosses the sky the sensor on the pyranometer remains always in shade. Consequently, the sensor is exposed only to diffuse light from above.

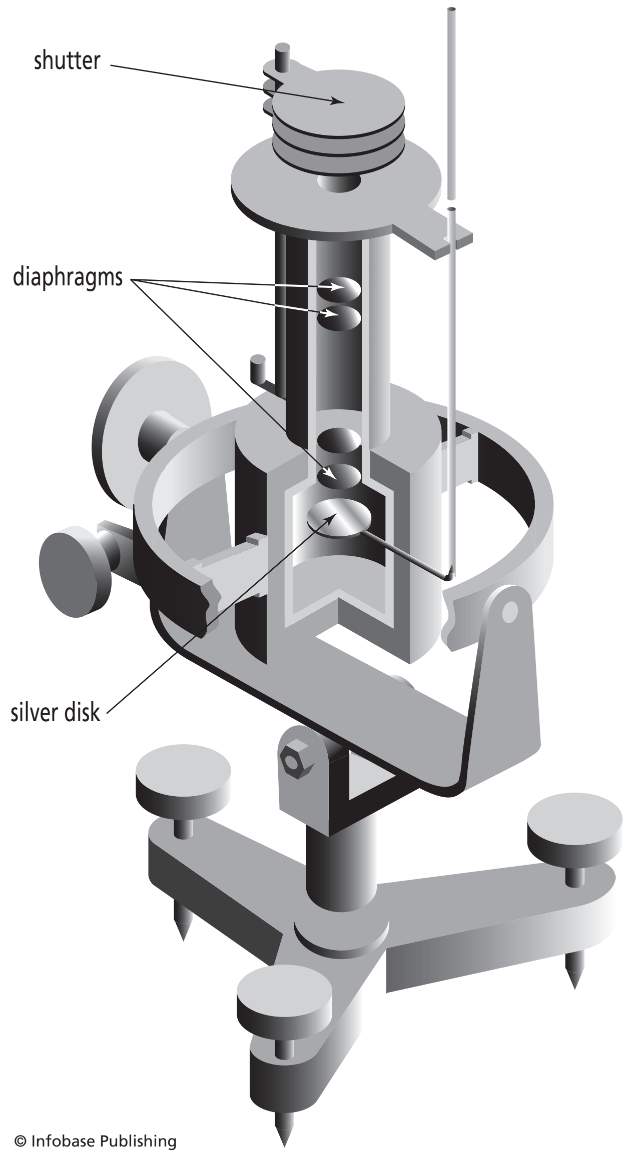
A pyranometer, also called a solarimeter, is fairly robust and more suitable for field use than the more accurate, but more delicate pyrheliometer. There are several pyranometer designs, but all are built around a sensor that detects the difference in temperature



A pyranometer measures solar radiation by comparing the temperatures of the adjacent black and white surface of a sensor. The sensor is contained in a glass sphere. This is the Eppley pyranometer.

between two adjacent materials. This may be achieved with a sensor consisting of two concentric rings, the inner one painted black to give it a low albedo and the outer one painted white to give it a high albedo. Up to 50 electrical sensors, in good contact with the underside of the rings, provide readings of the temperature difference between the high- and low-albedo surfaces. The sensor is enclosed in a glass bulb filled with dry air and designed either to allow radiation of all wavelengths to enter or to filter out particular wavelengths, such as those shorter than visible light. A pyranometer is usually set on the ground with its sensor surface horizontal and facing upward. By comparing the readings from two pyranometers, one facing vertically upward and the other vertically downward, it is possible to measure surface albedo. A pyrgeometer is a pyranometer that measures infrared radiation.

A pyrheliometer is a very sensitive instrument. It contains a blackened surface positioned at right angles to the sunlight. In the Abbot silver disk pyrheliometer, which is the one most often used in the United States, the receiving surface is a disk of blackened silver supported on fine, steel wires at the bottom of a copper tube. A very accurate THERMOMETER is attached to the underside of the disk. Diaphragms arranged at intervals in the tube allow only direct sunlight and light from the sky immediately adjacent to the Sun to enter. The instrument can be used only when the sky is completely cloudless within a 20° radius of the Sun. As well as measuring solar intensity, the pyrheliometer measures the rate at which this changes. For this purpose there is a triple shutter above the tube. The shutter opens and closes to expose and shade the disk alternately, at very precise two-minute intervals. The final readings must then be corrected for a standard air temperature of 68°F (20°C) and a disk temperature of 86°F (30°C). The Abbot pyrheliometer remains calibrated for many years and can be used to calibrate other instruments. Pyrheliometers are so sensitive and require such constant maintenance that they are used only at research laboratories and some of the principal weather stations.



The Abbot silver disk pyrheliometer measures the intensity of solar radiation. Sunlight enters past a system of shutters that open and close at two-minute intervals to allow the rate of change of solar intensity to be measured. Beneath the shutter, light passes along a tube containing diaphragms that exclude light that does not come directly from the Sun and the immediately adjacent sky. At the bottom of the tube the light falls on a blackened silver disk attached to a thermometer.

The Sun photometer measures the intensity of direct sunlight. It is held in the hand and pointed directly at the Sun. The Volz photometer is widely used to monitor air pollution. The Volz photometer was invented by Frederick E. Volz. It makes measurements that are defined by filters, that isolate particular wavebands. The measurements are not very precise, but relatively unskilled workers are able to take readings, and the sky does not need to be completely cloudless. The measurements indicate the amount of sunlight that is being scattered by haze and atmospheric particles.

solar spectrum The solar spectrum is the full range of electromagnetic radiation that emanates from the Sun. Solar radiation is emitted from the Sun's photosphere. The energy the radiation possesses is related to the TEMPERATURE of the photosphere by WIEN'S LAW. The photosphere is at about 10,960°F (6,070°C), and at this temperature the Sun radiates at every wavelength (*see* WAVE CHARACTERISTICS). The spectrum ranges from gamma rays with a wavelength of 10^{-5}–10^{-8} µm to radio waves with wavelengths of 1–10^{9} m. The Sun does not radiate with equal intensity at all wavelengths, however. Solar radiation reaches its maximum intensity at about 0.5 µm, which is the wavelength of green visible light.

A wave band is a range of wavelengths within which all electromagnetic radiation is similar in character. The electromagnetic spectrum contains seven wavebands, listed in the table below.

Gamma rays or gamma radiation, often written using the Greek letter γ (gamma), have a wavelength of 10^{-8} µm to 10^{-4} µm. This is shorter than the wavelength of X-rays, so gamma rays possess more energy than X-rays. Less than 1 percent of the radiation emitted by the Sun is at gamma wavelengths, and all the solar gamma radiation reaching the Earth is absorbed in the upper atmosphere. None penetrates to the surface.

X-rays have wavelengths of 10^{-5} µm to 10^{-3} µm. Less than 1 percent of the radiation emitted by the Sun is at X-ray wavelengths, and all of the solar X-rays reaching the Earth are absorbed in the upper atmosphere. None reach the surface.

Solar Wave Bands

wavelength (m)	name	frequency (Hz)
10^{-11}–10^{-14}	gamma rays	300–30 EHz
10^{-9}–10^{-11}	X-rays	3 EHz–300 PHz
10^{-7}–10^{-9}	ultraviolet	30–3 PHz
4–7 × 10^{-7}	visible light	1 PHz–300 THz
10^{-3}–10^{-6}	infrared	300 THz–300 GHz
10^{-1}–10^{-3}	microwave	300 GHz–300 MHz
1–10^{9}	radio	300 MHz–3 Hz

(EHz (exahertz) = 10^{18} hertz; PHz (petahertz) = 10^{15} hertz; THz (terahertz) = 10^{12} hertz; GHz (gigahertz) = 10^{9} hertz; MHz (megahertz) = 10^{6} hertz.)

Ultraviolet radiation (UV) has wavelengths between about 4 nanometers (nm) and 400 nm. This waveband is approximate, and there is overlap at either end, with X-rays at the short-wave end and visible violet light at the long-wave end. UV radiation at 400–300 nm is sometimes called near UV, UV at 300–200 nm is far UV, and UV at less than 200 nm is extreme UV or vacuum UV. The UV waveband is also divided into UV-A (315–380 nm), UV-B or soft UV (280–315 nm), and UV-C or hard UV (shorter than 280 nm).

Visible radiation is electromagnetic radiation to which the human eye is sensitive. It is shortwave radiation at wavelengths between 0.4 µm and 0.7 µm. At wavelengths shorter than 0.4 µm there is ultraviolet radiation and at wavelengths higher than 0.7 µm there is infrared radiation. The atmosphere is completely transparent to radiation at wavelengths between 0.35 µm and 0.8 µm. This means radiation passes through the atmosphere without being absorbed, but it is scattered by air molecules (*see* SCATTERING).

When visible white light passes through a prism, it divides into its constituent wavelengths. Light of different wavelengths then appears as a band of colors on a screen placed in a suitable position. The separation of the component wavelengths as white light passes through a prism is called dispersion. Violet light, which has the shortest wavelength, appears on the left, and red, with the longest wavelength, on the right. This is the arrangement of colors in the rainbow (*see* OPTICAL PHENOMENA). The wavelengths of visible light are:

violet 0.4 µm
indigo 0.43 µm
blue 0.46 µm
green 0.5 µm
yellow 0.57 µm
orange 0.6 µm
red 0.7 µm

Infrared radiation has a wavelength from 0.7 µm to 1 mm. This is longer than visible red light and shorter than microwaves. Certain atoms and molecules vibrate at frequencies within this waveband, and because of this they absorb infrared radiation at characteristic wavelengths (*see* ABSORPTION OF RADIATION). Certain substances can be identified by the infrared wavelength at which they absorb and absorption by some atmospheric gases produces the GREENHOUSE EFFECT.

In a real greenhouse, the glass absorbs and is therefore opaque to infrared radiation with a wavelength greater than 2 µm. All warm bodies emit infrared radiation. Although infrared is invisible to the human eye, human skin glows at infrared wavelengths. Far-infrared radiation has a wavelength greater than 15 µm. Near-infrared radiation has a wavelength of about 1–3 µm. WATER VAPOR is a very efficient absorber of near-infrared radiation. Thermal-infrared radiation has a wavelength of about 3–15 µm.

Microwaves are electromagnetic radiation with a wavelength of 1 mm to 10 cm (0.04–4 in). Many SATELLITE INSTRUMENTS use microwave radiation to measure sea ice and various features of the atmosphere.

Radio waves, at the far end of the solar spectrum, have the longest waves of all. Their wavelengths range from 1 meter (3.3 feet) to 1 million kilometers (621,000 miles).

solar-topographical theory A theory that explains past changes in climate in terms of variations in solar output and the formation and erosion of mountains. Mountains form when part of the Earth's crust is raised by volcanic activity (*see* VOLCANO) or as the result of a collision between two crustal plates (*see* PLATE TECTONICS). Their height then gradually decreases as material is lost by erosion.

The cycle of mountain-formation and erosion alters the elevation of the surface. It also affects the flow of air, tending to deflect air to the north or south of a mountain range, and forcing air to rise, and therefore cool and lose moisture, as it crosses high ground. Mountains have a clear climatic influence. So do variations in solar output, because they affect the amount of solar energy reaching the Earth. The theory considers variations of 10–20 percent to either side of the mean to be climatically significant.

solar wind A stream of protons, electrons, and some nuclei of elements heavier than HYDROGEN that flows like a wind, outward from the Sun. The wind is generated in the outermost region of the Sun, called the corona, where the temperature is so high that particles acquire sufficient energy to escape from the Sun's gravitational field.

The mean distance between the Earth and Sun, known as one astronomical unit (AU), is about 93.2 million miles (150 million km). At this distance the solar wind carries 16–165 protons per cubic inch (1–10 per cm^3) traveling at 220–440 miles per second (350–700 km/s). The solar wind deflects the tails of comets, so these always point away from the Sun, and it compresses the Earth's magnetic field. Interaction between the solar wind and the upper atmosphere produces auroras (*see* OPTICAL PHENOMENA). The intensity of the solar wind varies with the amount of SUNSPOT activity.

solstice The solstice is one of the two dates in each year when the difference in length between the hours of daylight and darkness is most extreme. The Arctic and Antarctic Circles, at latitudes 66.5°N and S (*see* AXIAL TILT), are defined as the latitudes at which the Sun does not rise above the horizon at the winter solstice and does not sink below it at the summer solstice. In latitudes higher than 66.5°, the periods of continuous darkness and daylight are longer than the one day at each solstice.

The solstices are also called midsummer day and midwinter day. At noon on midsummer day the Sun is directly overhead at the tropic in the summer hemisphere and at noon on midwinter day it is directly overhead at the other tropic. The solstices fall on 21–22 June and 22–23 December. The length of the day varies because the rotational axis of the Earth is tilted with respect to the PLANE OF THE ECLIPTIC, and it is this tilt that produces the SEASONS.

sonic boom The sound, like a clap of thunder, that is heard at the surface when an aircraft or other body flies at a speed greater than the SPEED OF SOUND. At subsonic speeds a moving object disturbs the air, sending out quite gentle waves of pressure that propagate in all directions, traveling at the speed of sound. These disturbances reach the surface continuously, and because they are slight and there is no sudden change in their intensity they make no sound. As the speed of the moving body approaches that of sound, and therefore of the pressure disturbances its motion produces, the pressure waves are confined in a decreasing volume. When the body exceeds the speed of sound and also the speed of its own pressure waves, the waves are behind the body and extend horizontally from it in a cone, called a Mach cone. The entire pressure field is contained within the Mach cone, where it produces a sudden, sharp increase in pressure, or SHOCK WAVE. An observer on the surface hears this as a loud bang when the edge of the Mach cone passes. Very large aircraft sometimes produce two sonic booms, one from the front of the aircraft and the other from the rear.

sounding Any measurement that is made through the column of air between the instrument and the level that is being monitored can be called a sounding. An instrument that makes a sounding is called a sounder.

Satellites usually carry sounders. These measure the amount of radiation being emitted at particular levels in the atmosphere. WEATHER BALLOONS also take soundings.

The word *sounding* was first used at sea to refer to the measurements of the depth of water that were made using a weighted rope. The word is derived from the French verb *sonder,* which comes from the Latin *subundare, sub-* meaning "under" and *unda* meaning "wave," so a sounding is literally a measurement taken from beneath the waves.

source The place at which a particular substance, usually a pollutant, is released into the environment, or the process by which it is released, is known as the source for that emission. For example, road transport is the source of CARBON DIOXIDE, NITROGEN OXIDES, and particulate matter (*see* AIR POLLUTION). The opposite of a source is a SINK.

Southern Oscillation At intervals of 1–5 years a change occurs in the distribution of air pressure over the equatorial South Pacific. This is called the Southern Oscillation.

Ordinarily, air rises in the region of Indonesia, where the sea-surface temperature is high. The air flows from west to east at high level, and descends near the South American coast. This produces low pressure over Indonesia and high pressure over the eastern South Pacific. Low-level winds blow from east to west, balancing the flow. From time to time this situation is reversed. Pressure is high over Indonesia, low over the eastern South Pacific, and air flows from east to west at high level and from west to east at low level. The change in direction of the surface wind constitutes an El Niño, the change between the two patterns of pressure distribution constitutes a southern oscillation, and the two together constitute an ENSO event.

The distribution of pressure over the South Pacific is recorded as the Southern Oscillation Index (SOI). This is a measure of the difference in sea-level atmospheric pressure between two monitoring stations, those most often used being at Darwin, Australia, and Tahiti, in the central South Pacific. A strongly negative SOI indicates a warming, and a strongly positive SOI indicates a cooling in the central and eastern equatorial South Pacific.

specific volume The specific volume is the volume that is occupied by a unit mass of a substance.

speed of sound Sound propagates as a SHOCK WAVE, so the speed with which a sound travels through a medium depends on the DENSITY and elastic modulus of the medium. The speed of sound through a medium is given by:

$$c = \sqrt{(E/\rho)}$$

where c is the speed of sound, E is the elastic modulus, and ρ is the density of the medium. The elastic modulus is the ratio of the stress applied to a body and the strain that stress produces.

For a gas, $E = \gamma p$, where γ is calculated from the HEAT CAPACITIES of the principal constituents and p is the pressure. This shows that the speed of sound in a gas is related to the temperature of the gas. This means that the speed of sound through a gas at a particular temperature can be expressed as:

$$c = c_0\sqrt{(1 + t/273)}$$

where c_0 is the speed of sound in the gas at 0°C, t is the temperature in °C, and dividing by 273 relates the Celsius TEMPERATURE SCALE to the Kelvin scale.

In the case of a liquid, E is the bulk modulus, which is the ratio of the pressure applied to the medium and the extent to which its volume decreases.

For a solid, the elastic modulus is known as Young's modulus, after the British physicist Thomas Young (1773–1829), who proposed it, and it is the ratio between the stress applied to the solid and the change in its length.

Sound travels through air at 68°F (20°C) at 769.5 MPH (344 m/s). It travels through water at 68°F (20°C) at 3,268 MPH (1,461 m/s) and through steel at 68°F (20°C) at 11,185 MPH (5,000 m/s).

spore A spore is a microscopically small organic structure produced by bacteria, fungi, and some plants, such as algae and ferns. It is capable of giving rise to a new individual without first fusing with another cell, but it does not contain an embryo of the new individual and is therefore quite different from a seed. Some bacteria survive in hostile environments for long periods as spores. Bacterial, fungal, and plant spores can be carried into the air to form part of the aerial plankton (*see* AEROSOL).

Spörer minimum The German solar astronomer Friedrich Wilhelm Gustav Spörer (1822–95) identified a period from 1400 to 1510 during which very few SUNSPOTS were observed. Spörer described the phenomenon in an article published in 1889, which attracted the attention of the English astronomer Edward Walter Maunder (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). The American solar astronomer John A. Eddy (born 1931) named the period the Spörer minimum.

Like the MAUNDER MINIMUM, the Spörer minimum was known as the LITTLE ICE AGE. Temperatures were abnormally low. Norse settlers were forced to leave Greenland because their crops failed and the SEA ICE failed to thaw, so they could not fish. Famine increased in many parts of the world and in the winter of 1422–23 ice covered the entire surface of the Baltic Sea.

Further Reading

Geerts, B., and E. Linacre. "Sunspots and Climate." Available online. URL: www-das.uwyo.edu/~geerts/cwx/notes/chap02/sunspots.html. Accessed February 1, 2006.

squall A squall is a sudden, brief STORM in which the WIND SPEED increases by up to 50 percent, then dies away more slowly. For a storm to be described as a squall in the United States, the wind must reach 16 knots (18.4 MPH, 30 km/h) or higher for at least two minutes. The wind speed may reach 30–60 MPH (50–100 km/h) in a severe squall and speeds of 100 MPH (160 km/h) have been recorded.

A squall that is accompanied by a short period of heavy rain is called a rain squall. The rain falls from cumuliform cloud, commonly cumulonimbus (*see* CLOUD TYPES). It is carried by wind that blows outward from the center of the storm, and it often precedes the rain associated with a THUNDERSTORM.

A series of squalls sometimes occurs along a line known as a squall line. This is a series of very vigorous cumulonimbus clouds that merge to form a continuous line which is often up to 600 miles (965 km) long and that advances at right angles to the line itself. Cloud formation begins along a cold FRONT, where moist air in the warm sector ahead of the front is being undercut and lifted by the advancing cold air. This produces a number of severe local storms. The clouds grow very tall in the unstable air (*see* STABILITY OF AIR), often penetrating through the tropopause (*see* ATMOSPHERIC STRUCTURE). A weak INVERSION in the warm sector restricts the development of CONVECTION cells except at the front itself.

A squall line in Pamlico Sound, North Carolina, with a sail boat heading toward it. ***(Michael Halminski, Historic NWS Collection)***

Wind speed increases with height, and the speed of the wind in the middle troposphere determines the speed with which the clouds move. Consequently, the upper part of each cloud overtakes its base, so the cloud overhangs its own base. Warm, moist air ahead of the cloud is then swept up into the convection cell inside it. The warm air is lifted to the free convection level and then rises rapidly to the top of the cloud, where the wind reaches its maximum speed and the cloud is drawn into an anvil shape. Where the base of the anvil meets the main body of the cloud, EDDIES produced by the vertical air currents produce a characteristic roll of cloud called a squall cloud, often with mammatus.

CONDENSATION in the updraft of air produces PRECIPITATION. This falls from the trailing edge of the cloud. Some of the water droplets evaporate in the drier air below the cloud. This chills the adjacent air, and falling RAINDROPS drag cold air down with them, causing a DOWNDRAFT. The downdraft produces a very local region of slightly raised surface atmospheric pressure. Part of the downdraft flows beneath the cloud and below the updraft. The updraft and downdraft meet at the leading edge of the cloud, where they produce strong GUSTS of wind along a line known as the gust front.

The gust front cuts beneath the warm air ahead of the cloud, lifting it into the updraft. Each individual cumulonimbus contains a single convection cell that lasts for only an hour or two before exhausting its supply of moisture and dissipating. Its gust front, however, scoops up moist air in front and to the right, which produces a new cloud. As soon as a cloud attains its maximum development it begins to dissipate, at the same time triggering the development of a new cloud on its right front.

The vigor with which the gust front is able to shovel up warm, moist air causes the line of clouds to move faster than the cold front which initiated their formation. The squall line then becomes detached from the cold front, advancing ahead of it into the warm sector and moving at 10°–20° to the right of the wind direction in the middle troposphere. Behind the local high-pressure band associated with the downdraft, there is a region of low pressure, called the wake low (*see* THUNDERSTORM).

In a cumulonimbus cloud containing a single convection cell, the updrafts and downdrafts conflict. This limits the development of the cloud and contributes to its dissolution. Along a squall line, however, the updrafts and downdrafts augment each other. This allows a squall line to last for several days, rather than the hour or two of an individual cloud, and to produce storms of much greater ferocity. TORNADOES often form along squall lines.

Squall lines are especially common in the central and eastern United States.

A squall in tropical or subtropical seas that occurs suddenly and without the prior appearance of a squall cloud is known as a white squall. The only indication of its approach is a line of white water caused by the wind.

stability index A stability index is one of a series of values that are used to summarize the STABILITY OF AIR and the severity of the THUNDERSTORMS, up to and including TORNADOES, that varying degrees of atmospheric instability are likely to generate. Stability indices must be used with caution, because they do not apply to every situation. The most commonly used indices are the K Index (K), Lifted Index (LI), Showalter Stability Index (SSI), Total Totals (TT), SWEAT Index, and Deep Convective Index (DCI). Each index produces a single numerical value that indicates either the degree of instability or the probability of severe storms. The relationship between K values and the probability of severe thunderstorms is shown in the table above.

K Index

K Index	Probability of a thunderstorm
<15	0%
15–20	<20%
21–25	20–40%
26–30	40–60%
31–35	60–80%
36–40	80–90%
>40	nearly 100%

K measures the potential for thunderstorms from the LAPSE RATE and atmospheric moisture. LI and SSI both measure convective instability but to different heights. TT has two components, Vertical Totals (VT) and Cross Totals (CT), which measure static stability and DEW point temperature respectively at particular levels. SWEAT (Severe Weather Threat Index) takes a number of factors into account. DCI combines equivalent potential temperature (*see* PARCEL OF AIR) and instability.

The introduction of powerful computers has allowed meteorologists to calculate the more complicated convective available potential energy (CAPE). This has reduced their reliance on stability indices.

stability of air The tendency of a PARCEL OF AIR to possess neutral BUOYANCY, so that it remains at a constant height, is described as the stability of that air. Air with neutral or negative buoyancy is said to be stable and air with positive buoyancy is unstable. Whether air is stable or unstable depends on the difference between the environmental LAPSE RATE (ELR) and the adiabatic lapse rate (*see* ADIABAT). This difference is known as the POTENTIAL TEMPERATURE gradient, because it refers to a rate of change, or gradient, in the potential temperature of the air.

Neutral stability is the condition in which the atmosphere is stratified, and the potential temperature neither increases nor decreases with height. If a parcel of air moves vertically in either direction, it will enter a region where its DENSITY is similar to that of the surrounding air. Consequently, gravity will not restore it to its original level and it will remain where it is.

The amount by which the air temperature decreases between the surface and the tropopause (*see* ATMOSPHERIC STRUCTURE) determines the ELR. The ELR is assumed to remain constant throughout the troposphere. The temperature at the tropopause is always about -74°F (-59°C). If, then, the surface temperature is 59°F (15°C), and the height of the tropopause is 36,000 feet (11 km), the ELR will be about 3.7°F per 1,000 feet (6.7°C per km). This is an average value for the ELR, based on the fact that the mean surface temperature over the whole world is 59°F (15°C). The actual ELR varies with every change in the surface temperature. For example, if the surface temperature is 32°F (0°C), the ELR will be 2.9°F per 1,000 feet (5.4°C per km), but if the surface temperature is 80°F (27°C), the ELR will be 4.3°F per 1,000 feet (7.8°C per km).

Suppose unsaturated air at 59°F (15°C) is forced to rise. It will cool at the dry adiabatic lapse rate (DALR) of 5.38°F per 1,000 feet (9.8°C per km). This is greater than the ELR. Consequently, the temperature of the rising air decreases faster than the ELR. At any height the rising air will be cooler and denser than the surrounding air, so it will sink back to the level at which it is at the same temperature and density as the air around it. This air will be stable. The most stable condition of all occurs in a layer of air that lies beneath an INVERSION.

If the SALR is greater than the ELR, rising air will always be cooler and denser than the surrounding air, even if the air is saturated. This condition is called absolute stability. If a parcel of absolutely stable air is made to rise, at first it will cool at the dry adiabatic lapse rate (DALR). This is higher than the SALR and therefore it is also higher than the ELR. The rising air will quickly reach a level at which it is cooler than the surrounding air and so it will sink once more. Even if it is forced to rise high enough for its WATER VAPOR to start to condense, for example by being carried across a mountain, it will still tend to sink. CONDENSATION of its water vapor will release LATENT HEAT of condensation, warming the air and altering its lapse rate from the DALR to the SALR, but this is still greater than the ELR, so the rising air will always be cooler than the air around it.

When cold, stable air lies beneath a layer of potentially warmer air, a high föhn, also called a stable-air föhn, may develop. This situation occurs when cold, stable air moves against a mountain range. In stable air the upper layer is at a higher potential temperature than the lower layer. The upper layer of air spills over the mountains and descends, warming adiabatically as it does so. A high föhn can also develop when subsiding air in an ANTICYCLONE is chilled by a cold land or sea surface.

Static stability, also called convective stability, is the condition in which the atmosphere is stratified so that its density decreases with height and buoyancy increases. The potential temperature increases with height. If a parcel of air rises by CONVECTION, it enters a region where it is denser, and therefore heavier, than the surrounding air, so gravity will cause it to sink back to its original level. If the parcel should sink, it enters a region where it is less dense, and lighter, than the surrounding air, so it will rise to its original level. When the atmosphere is not statically stable, it may be neutrally stable or convectively unstable.

If the air is moist, it may reach a height at which it becomes saturated and water vapor starts to condense. Condensation will release latent heat, reducing the rate of cooling to the SALR. This is a slower rate of cooling than the ELR, so air cooling at the SALR will always be warmer and less dense than the air around it. It will therefore continue to rise. This air will be unstable. Instability is the tendency of air that has begun to rise to continue to rise.

Because the ELR is greater when the surface air is warm than it is when the surface air is cold, air is more likely to be unstable in warm weather than it is in cold weather. On really cold days in winter the air is usually very stable, because the ELR is low. When the surface temperature is -10°F (-23°C), the ELR is only 1.8°F per 1,000 feet (3.3°C per km), which is much lower than the SALR.

Any line that is not associated with a frontal system (*see* FRONT) and along which the air is subject to vigorous convection and is therefore unstable is called an instability line. If the instability leads to the formation of active cumulonimbus clouds (*see* CLOUD TYPES) and THUNDERSTORMS, the line is known as a SQUALL line.

The opposite of absolute stability is absolute instability, which is the condition of air when the ELR is greater than the DALR. As it rises, a parcel of absolutely unstable air will cool at the DALR, but because this is a slower rate of cooling than the ELR it will always be warmer than the surrounding air. If the air contains water vapor, it may reach a height at which this starts to condense to form cloud. The release of latent heat of condensation will warm the air, reducing the lapse rate from the DALR to the SALR. The difference between the ELR and the SALR is greater than that between the ELR and DALR, so the instability of the air will increase.

Being always warmer than the air immediately above it, the rising unstable air will retain its buoyancy and will continue to rise. Its rise will finally be checked when it reaches a height at which the ELR decreases to less than the SALR or to less than the DALR in the dry air above the cloud top or if no cloud has formed.

These conditions are likeliest to occur on very hot days. Air that is heated strongly from the ground then forms a layer that is at a much higher temperature than the air above it, producing a very steep ELR. Clouds that form in absolutely unstable air are seldom very deep, because the layer of very warm air that causes the instability is usually quite shallow, so the steep ELR does not extend very high. Consequently, absolutely unstable air does not usually produce STORMS or even SHOWERS.

Convective instability, also known as potential instability and static instability, is caused by convection. It happens when the atmosphere is stratified, but the potential temperature decreases with height, and as a layer of moist air rises, the lower part of the layer becomes saturated (*see* SATURATION) before the upper part. Rising air in the lowest layer, which is not yet saturated, is then cooling at the DALR, saturated air in the layer above it is cooling at the shallower SALR, and air in the uppermost layer is cooling at the DALR. If the lapse rate through the entire layer of rising air is greater than the SALR, saturated air will always be rising into air that is cooler. It will always be less dense, and therefore lighter, than the surrounding air. Consequently, its upward movement will accelerate. The entire layer will then be unstable and may overturn. As it continues to rise, however, the air will also cool and its density will increase, so eventually the atmosphere will become statically stable.

When the ELR is greater than the SALR but smaller than the DALR, the condition is known as conditional instability. Unsaturated air will not rise unless it is forced to do so, for example by crossing a mountain, because if it does it will cool at the DALR. This is greater than the ELR, and so the rising air will immediately be cooler than the surrounding air and will tend to sink again. While it remains unsaturated the air is stable.

Should it be forced to rise high enough for it to reach its lifting condensation level (*see* CONDENSATION), however, the water vapor it carries will start to condense into cloud droplets. This will release latent heat of condensation, warming the air and slowing its lapse rate from the DALR to the SALR. This is lower than the ELR, so the rising air will always be warmer than the surrounding air because it is cooling more slowly. Being warmer, it will remain buoyant and will continue to rise. The air is then unstable.

Some outside force must compel the air to rise before it will change from being stable to being unstable. This force is the condition needed to trigger instability, which is why the air is said to be "conditionally" unstable. This is the commonest type of instability.

The level of free convection is the height at which a parcel of air that is being forced to rise through a conditionally unstable atmosphere changes from being cooler than the surrounding air to being warmer than it. While it is near the surface, the parcel of air is moist, but not saturated. As it is forced to rise through air that is warmer than itself it cools at the DALR until it reaches the lifting condensation level, beyond which it cools at the SALR. Its temperature then decreases with height more slowly than that of the surrounding air, where the ELR is close to the DALR, until a level is reached at which it is warmer than the surrounding air. Beyond that point the parcel of air is unstable and continues to rise without the need of forcing until it reaches a second level, where its temperature is once more lower than that of the surrounding air and it becomes stable.

Latent instability is the condition in which a parcel of air that acquires sufficient KINETIC ENERGY to rise through a layer of stable air becomes unstable once it is above the level of free convection. It is a type of conditional instability that develops only if a parcel of air rises to the critical level.

There is a different type of conditional instability, known as conditional instability of the second kind (CISK). CISK leads to the formation of large, long-lived clusters of cumulonimbus cloud over tropical oceans.

Ordinarily, conditional instability produces cumuliform clouds that are isolated because each cloud is built by a convection cell that utilizes all the moisture and energy in its immediate vicinity, thus preventing the formation of another cloud nearby.

In the TROPICS it is possible for conditional instability to be intensified by horizontal air movements. This happens when there is an area of low pressure covering a surface area about 600 miles (1,000 km) across and the air is conditionally unstable. Air converges from all sides toward the low-pressure region (*see* STREAMLINE). Friction with the surface slows the air, reducing the magnitude of the CORIOLIS EFFECT so the PRESSURE GRADIENT FORCE becomes dominant. The converging air enters the low-pressure region and rises at the center. Alternatively, an ATMOSPHERIC WAVE may move across the area. Such waves often produce convergence in some places and divergence in others.

Convergence triggers convection. At the same time, the converging air is warm and moist, so it feeds moisture into the convection cells. It also pushes the developing clouds closer together. Latent heat is released as water vapor condenses in the rising air. This warms the air, fueling further convection. Divergence above the clouds reduces the amount of air beneath and therefore reduces the surface pressure. This intensifies and sustains the low-pressure system.

This alternative type of conditional instability is involved in the formation of TROPICAL CYCLONES. Meteorologists Jule Charney and Arnt Eliassen were the first scientists to recognize the difference between it and ordinary conditional instability in 1964. Katsuyuki Ooyama also described it and called it "conditional instability of the second kind," the name it has retained. Ordinary conditional instability is sometimes called conditional instability of the first kind to help distinguish the two types.

There are ways to test the stability of air. The parcel method calculates the consequences of displacing particular parcels of air. It is assumed that only those parcels are affected, but in fact their stability is similar to that of the larger body of air around them. The slice method takes account of air that is moving vertically in both directions through a slice of air.

stade (**stadial**) A period of cold that occurs during a GLACIAL PERIOD. It may be marked by a change in the vegetation of ice-free areas or by the advance of ICE SHEETS.

stage A series of sediments, fossils, or plant remains that are found in a particular place and that indicate the climatic conditions which obtained at the time they were deposited. The stage is named after the place where the evidence for it was first discovered. For example, the Hoxnian INTERGLACIAL was identified by deposits found at the village of Hoxne, in Suffolk, England, and is known as the Hoxnian stage.

standard artillery atmosphere A standard artillery atmosphere is a set of hypothetical values that are used in calculations of the trajectory of missiles through the air (ballistic calculations). These values assume there is no wind, the surface temperature is 59°F (15°C), surface pressure is 1000 mb (14.5 lb/in^2, 29.5 inches of mercury), surface relative HUMIDITY is 78 percent, and the LAPSE RATE directly relates air DENSITY to altitude.

A standard artillery zone is a layer of the standard artillery atmosphere that is of a specified thickness and at a specified altitude.

Statherian The most recent of the four periods of the PALEOPROTEROZOIC era of the Earth's history, the Statherian period began 1,800 million years ago and ended 1,600 million years ago. *See* APPENDIX V: GEOLOGIC TIMESCALE.

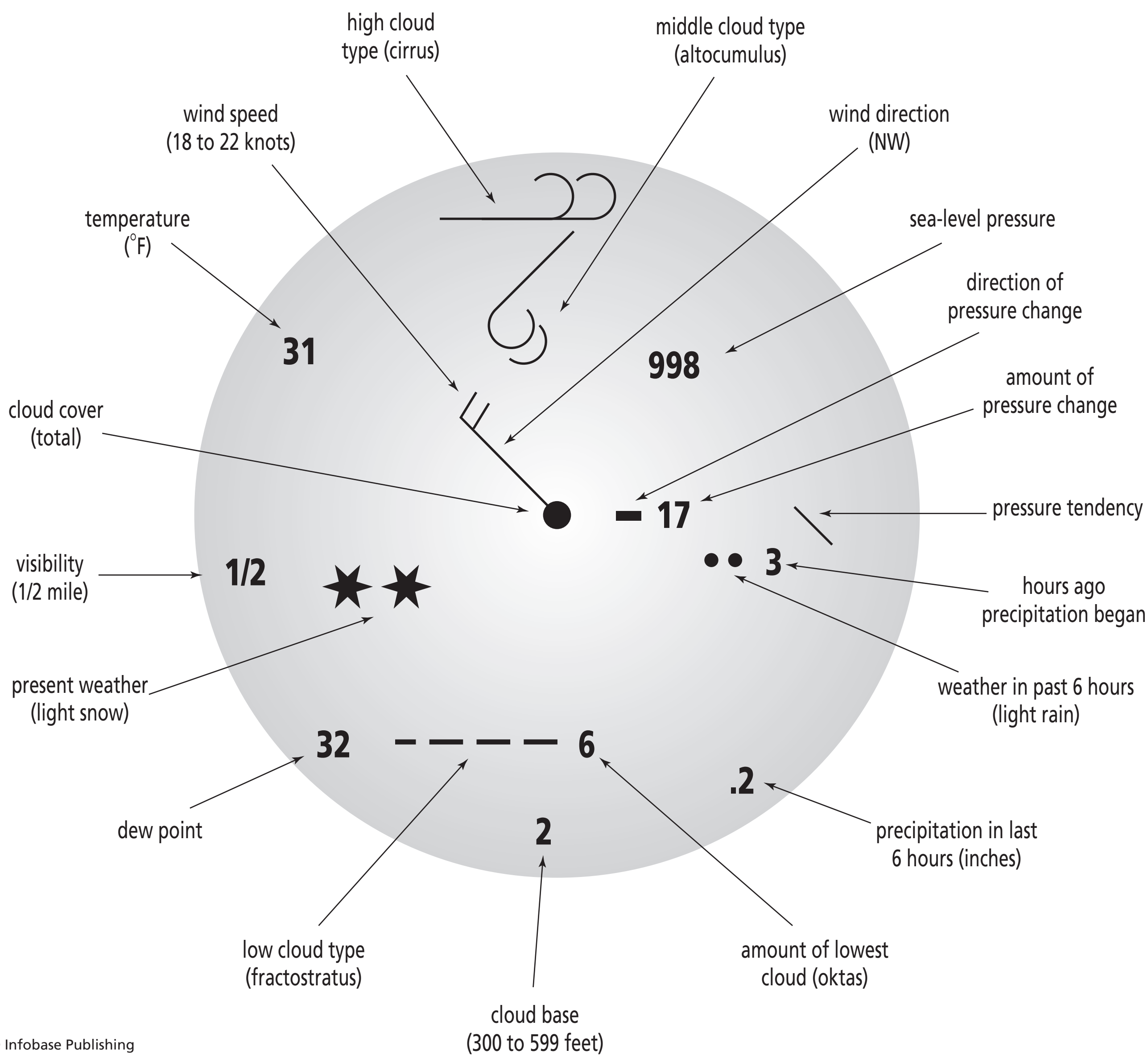
static electricity An electrical charge that is at rest, so it does not flow. A charge that does not flow is called an electrostatic charge.

One region, such as the upper part of a cumulonimbus cloud (*see* CLOUD TYPES), bears a positive charge and another, such as the lower part of the same cloud, bears a negative charge, but the two areas of charge are separated by an area that is electrically neutral. Consequently, no electrons move from the positive to negative areas. When the charge has accumulated sufficiently to overcome the insulating effect of the neutral region, the static charge is discharged in a spark, in this case a flash of LIGHTNING.

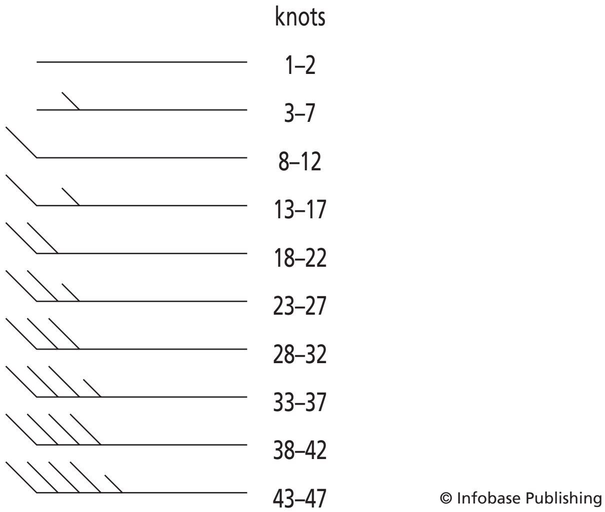
station model The formalized diagram that is used to report observations from a weather station is called a station model. The diagram uses standard symbols to represent cloud, PRECIPITATION, and wind direction and speed. Other information is given in numbers. Each item of information occupies a particular position around the station, which is represented by a circle at the center.

The central circle, called the station circle, is drawn in its geographic position on a weather chart, and the other information is positioned around it. Whether the station circle is open or partly or completely black indicates the amount of cloud cover.

A line from the station circle indicates the wind direction and lines or pennants at the end of this line indicate the WIND SPEED. The lines, or barbs, are drawn at an angle at the end of a longer line. Barbs are used only for wind speeds up to 47 knots (54 MPH, 87 km/h). The other end of the shaft to which the barb is attached joins the station circle, and the angle at which it projects indicates the wind direction. A pennant is a triangular symbol, resembling a pennant flag, that is used to indicate wind speeds greater than 48 knots



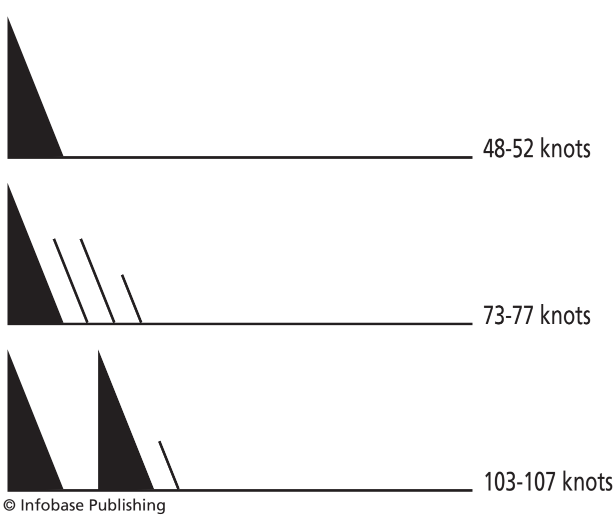
A station model is the formal arrangement of numbers and symbols that is plotted on a weather chart to indicate the conditions reported from a particular weather station.



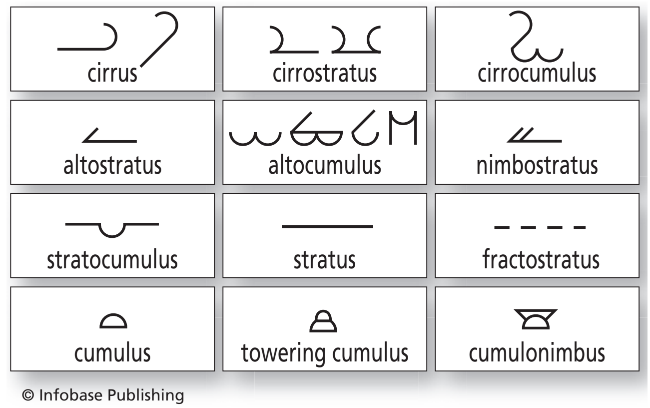
Barbs are short lines drawn on the shaft indicating wind direction on a station model. The number of long and short barbs indicates the wind speed, which is given in knots.

(55 MPH, 89 km/h). It is drawn so that the shaft of the pennant indicates the wind direction. The barbs and pointed tips of the pennants point toward the region of low pressure.

Cloud symbols are a set of ideograms used to indicate cloud types. There are symbols for all 10 cloud genera (*see* CLOUD CLASSIFICATION) as well as two more, for fractostratus and towering cumulus (*see* CLOUD TYPES).



Pennants are triangular symbols, resembling pennant flags, which are used on a station model to indicate wind speeds higher than those represented by barbs. These are three examples.

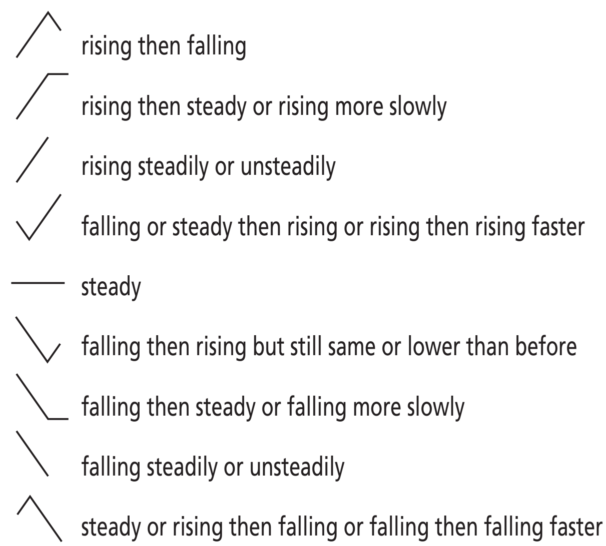


There are 12 cloud symbols. These represent the 10 cloud genera, plus fractostratus and towering cumulus.

The CLOUD BASE is reported in a code that translates to a range of heights (in feet) and the amount of the lowest cloud is given in oktas (*see* CLOUD AMOUNTS.) Symbols are also used to indicate the present and past weather.

In addition, the model shows the sea-level AIR PRESSURE in millibars. The atmospheric pressure that is measured at the station elevation is called the station pressure or surface pressure. The station elevation is the vertical distance between a weather station and mean sea level. This is measured for a particular point at the station and is used as a reference DATUM for calculating atmospheric pressure. The station barometers show pressure at the station, but because pressure varies with elevation this is converted to sea-level pressure, and it is the sea-level pressure that is reported. Since all stations report sea-level pressure, their reports can be compared directly and isobars (*see* ISO-) can be plotted without a need for further corrections.

The lowest sea-level pressure ever recorded (in the eye of typhoon Tip; *see* APPENDIX II: TROPICAL CYCLONES AND TROPICAL STORMS) was 870 mb, and the highest (recorded on December 31, 1968, at Agata, Siberia, Russia) was 1,083.8 mb. In reporting sea-level pressure, therefore, the thousands and hundreds units (8, 9, or 10) can be assumed. They and also the decimal point can then be omitted for the sake of brevity, so the pressure is always represented by a three-digit number. For example, a pressure of 999.8 mb is reported as 998 (that is, (9)**99**(.)**8**), and a pressure of 1012.4 as 124 (that is, (10)**12**(.)**4**). The model also reports whether the pressure has increased (+) or has decreased (-) over the past six hours, the amount by which it has changed



Barometric tendency is shown on a station model by symbols that indicate the way atmospheric pressure has changed over the reporting period.

(in tenths of a millibar), and the present barometric tendency. The barometric tendency, also called the air pressure tendency and pressure tendency, is the direction in which the atmospheric pressure has changed at a weather station since the last time it was reported.

TEMPERATURE and DEW point are reported (in degrees Fahrenheit or Celsius). Horizontal VISIBILITY is given in miles or kilometers. If there is precipitation, the number of hours since it began and the amount of precipitation in the last six hours are reported.

Station models are updated every six hours.

Stefan-Boltzmann law The Stefan-Boltzmann law is the physical law that relates the amount of radiant energy a body emits to its temperature. The law applies to BLACKBODIES, including the Sun and Earth, and shows that the amount of radiation emitted is proportional to the fourth power of the temperature of the body.

The law is expressed as: $E = \sigma T^4$, where E is the amount of radiation emitted, T is the temperature, and σ is the Stefan-Boltzmann constant. The temperature is in kelvins (*see* UNITS OF MEASUREMENT) and the energy units are watts per square meter (W/m^2).

The Stefan-Boltzmann constant (σ) is the amount of radiant energy released by a blackbody. This is equal to 5.67×10^{-8} $W/m^2/K^4$ (watts per square meter per kelvin to the fourth power).

The law and constant were discovered in 1879 by the Austrian physicist Josef Stefan (1835–93; *see* APPENDIX I: BIOGRAPHICAL ENTRIES), and at first they were known as Stefan's law and constant. In 1884, the Austrian physicist Ludwig Eduard Boltzmann (1844–1906), Stefan's former student, showed that the law holds only for blackbodies, and his name was added to that of the law and constant. Stefan used the law to make the first fairly accurate estimate of the temperature of the photosphere (visible surface) of the Sun, as 10,800°F (6,000°C).

stem flow PRECIPITATION that falls onto vegetation and reaches the ground by running down the stems of plants is called stem flow. The amount of water reaching the ground as a result of stem flow depends on the total amount of precipitation intercepted by the plants, the amount that evaporates from the leaves, and the amount that evaporates from the stem during stem flow.

If the vegetation is dry when precipitation commences, the plants will intercept a high proportion of the precipitation, especially if the precipitation is light. Water coating the leaves will immediately begin to evaporate, the rate of EVAPORATION depending on the temperature. In Brazilian forests, for example, about 20 percent of the rain falling onto the leaves evaporates, and almost all the rain falling on them evaporates from the leaves of some forests growing in Mediterranean climates, so there is no stem flow. The amount of stem flow and water dripping from leaves must be measured very precisely in studies of the amount of precipitation that reaches the ground in forests.

Stenian The third and final period of the MESOPROTEROZOIC era of the Earth's history, the Stenian began 1,200 million years ago and ended 1,000 million years ago. During the Stenian most of the world's continents came together and joined, forming a supercontinent called Rodinia (*see* PLATE TECTONICS). Very little is known about conditions on Earth so long ago. *See* APPENDIX V: GEOLOGIC TIMESCALE.

Stevenson screen The container that houses the THERMOMETERS and HYGROMETERS or HYGROGRAPHS used at a weather station is named after Thomas Stevenson (1818–87), who invented it. Stevenson was an amateur meteorologist, but nevertheless he had a professional interest in the weather. He was a civil engineer, and the Stevenson family firm specialized in building lighthouses throughout the world. Stevenson was born in Edinburgh, a city that he helped to make into a world center for the science of lighthouse lenses and lights. That is also where his son was born, the author Robert Louis Stevenson (1850–94).

The Stevenson screen is a box with louvered walls on all its four sides. The walls and top are of double thickness, with the louver strips forming inverted V shapes in cross section. The screen is painted white and stands on legs that raise it so that the bulbs of its thermometers are about 4 feet (1.25 m) above the ground. At this height the thermometers register air temperature, which is also called shelter temperature or surface temperature. This height is the lowest at which a thermometer will give a reliable reading for the temperature that is experienced by people and that is true for a large surrounding area. The temperature at this height is influenced, but not overwhelmed, by variations in temperature closer to the ground. Ground-level temperatures often change markedly over short distances, so simply moving the instrument to a different location nearby could alter thermometer readings significantly.

A Stevenson screen is a container of standard construction and dimensions that is used to house the thermometers at a weather station. The screen is painted white, has double-louvered sides, and is sited in the open and well clear of the ground.

The purpose of the white paint and louvered construction is to shield the instruments from exposure to direct radiation without isolating them from the air they are to monitor. It is because of the shielding it provides that the container is called a screen.

Thermometers are sensitive to sunlight, which warms them directly, and they are also affected by radiation rising from the ground. The white color reflects most of the radiation that falls on it, and the thick, wooden walls and floor of the screen insulate the air inside. For added protection the screen is positioned so that access to the instruments is from a door on the side facing away from the equator (the northern side in the Northern Hemisphere). This prevents the Sun from shining into the screen while readings are being taken. The louvered construction of the sides allows air to circulate, so the temperature being measured is that of the air outside the screen.

Standardizing both the construction and the siting of Stevenson screens means that all weather stations are obtaining readings under similar conditions. This makes the readings directly comparable.

The disadvantage of the Stevenson screen is that although the double-louvered walls permit air to circulate, the ventilation inside the screen is poor. In hot weather the temperature inside the box can be a degree or more higher than the air temperature outside. Some screens are fitted with fans to improve ventilation.

A Stevenson screen usually contains four thermometers. These are the wet-bulb thermometer and dry-bulb thermometer used to calculate relative HUMIDITY and DEW point temperature, and the dry-bulb maximum and minimum thermometers. The wet-bulb and dry-bulb thermometers are mounted vertically and the maximum and minimum thermometers horizontally.

A Bilham screen is a small container with louvered sides like a Stevenson screen that contains a wet-bulb thermometer and dry-bulb thermometer mounted vertically and a maximum thermometer and a minimum thermometer mounted horizontally.

stochastic A stochastic system is one that obeys statistical laws. The future behavior of a stochastic system cannot be predicted precisely, but its probable future behavior can be calculated on the basis of its known past behavior.

Modern weather forecasters adopt an approach that is partly stochastic and partly deterministic (*see* DETERMINISM). They recognize that while natural laws certainly determine the behavior of the atmosphere, it is impossible to know the condition of the atmosphere in the detail required for an entirely deterministic calculation. Consequently, they make the best calculation they can, but qualify it by taking account of the way similar conditions developed in the past. This allows them to estimate the probability of a particular weather pattern emerging. A probabilistic forecast makes allowance for the chaotic behavior of weather systems, but because of CHAOS its reliability is inversely proportional to the forecast period.

stochastic resonance Stochastic resonance is the observable effect that results when a STOCHASTIC process acts in the same sense as a natural cycle that is too weak to produce any effect by itself. Stochastic processes ordinarily appear as noise, and scientists try to remove them in order to detect signals. If the signals are extremely weak, however, a stochastic process may reinforce them. The two are then said to resonate, and because it is the stochastic process that produces the resonance, it is called stochastic resonance.

OXYGEN isotope records from the GREENLAND ICECORE PROJECT indicate that stochastic resonance underlies a 1,500-year climate cycle, the most recent manifestation of which was the LITTLE ICE AGE. Stochastic resonance may also be responsible for the onset of GLACIAL PERIODS and INTERGLACIALS at intervals of approximately 100,000 years. These are driven by the MILANKOVITCH CYCLES, but changes in the ORBIT and rotation of the Earth are believed to be too small to account for ice ages. If stochastic warming and cooling of the climate coincide with the peaks and troughs of the Milankovitch cycles, their additional effect would be enough to trigger the observed effects.

Stochastic processes are unreliable and cannot be expected to coincide with every phase in a regular natural cycle. Sometimes resonance should occur and sometimes not. The result of this would be that the observed effect occurs most often at the peak or trough of one cycle, but sometimes skips one cycle and more rarely skips two. Very rarely, an event occurs at less than a complete number of cycles since the preceding one. This pattern is what emerges from the ICE CORE record.

In the case of the 1,500-year cycle, this means that most cool episodes resembling the Little Ice Age happen at intervals of 1,500 years, but some occur every 3,000 years and a few every 4,500 years. Similarly, ice ages and interglacials often begin every 100,000 years, but not always. Sometimes 200,000 years can pass without either.

Stokes's law Stokes's law describes the factors that determine the magnitude of the friction experienced by a spherical body (such as a RAINDROP or hailstone, *see* HAIL) falling by gravity through a viscous medium (such as air). Friction (*F)* is given by:

$$F = 6\pi r\eta v$$

where r is the radius of the body, v is its velocity, and π is the VISCOSITY of the medium.

From Stokes's law it is possible to calculate the TERMINAL VELOCITY (V) of the body as:

$$V = 2g\,(\rho_p - \rho_a)\,r^2 \div 9\,\eta$$

where g is the acceleration due to gravity (32.18 ft/s^2 = 9.807 m/s^2), ρ_p is the density of the body, and ρ_a is the density of the medium through which it is falling.

A very small water droplet, with a diameter of about 0.0004 inch (10 µm), has a terminal velocity falling through air of about 0.03 feet per second (10^{-3} m/s). A drop 100 times larger, with a diameter of about 0.04 inch (1 mm), will fall at about 33 ft/s (10 m/s).

The relationship was discovered between 1845 and 1850 by the Irish physicist Sir George Gabriel Stokes (1819–1903; *see* APPENDIX I: BIOGRAPHICAL ENTRIES).

stomata (sing. stoma) Stomata are the pores in the surface of plant leaves, especially on the undersides, through which gases are exchanged. In most plants, stomata are open during the day and closed at night. Each stoma can be opened and closed by the expansion and contraction of two guard cells at its mouth.

When the stomata are open, air can enter the cell beneath to provide CARBON DIOXIDE for PHOTOSYNTHESIS and OXYGEN, a by-product of photosynthesis, can leave. WATER VAPOR also escapes while the stomata are open. The loss of moisture in this way is called TRANSPIRATION.

Plants adapted to dry climates usually minimize the time during which their stomata are open. Some desert plants (called CAM plants) open their stomata at night and store the carbon dioxide they absorb until daybreak, after which photosynthesis proceeds with the stomata remaining closed.

storm In the BEAUFORT WIND SCALE, a storm is a wind of force 11, which blows at 64–75 MPH (103–121 km/h). In the original scale, devised for use at sea, a force 11 wind was defined as "or that which would reduce her to storm staysails." On land, a storm uproots trees and blows them some distance, and overturns cars.

Storm detection comprises the identification of conditions that are leading to the development of a storm, followed by its observation and tracking. As techniques have improved, the importance of storm detection has increased. Detection involves recognizing particular characteristics, especially wind strength and PRECIPITATION, that indicate the type of storm and measuring or calculating the area the storm covers. Balloon sondes (*see* WEATHER BALLOON), flights by aircraft equipped with meteorological instruments, RADAR including Doppler radar, and satellite images are used to detect and then study storms.

A windstorm is a storm in which the most significant characteristic is a very strong wind. In the TROPICS the areas of low pressure that produce such storms are not usually of frontal origin. Tropical windstorms can grow into TROPICAL CYCLONES. Windstorms in middle latitudes are often associated with deep frontal DEPRESSIONS, and they can be severe. A series of windstorms crossed France and Belgium for three days between Christmas 1999 and the New Year. Winds gusted to 105 MPH (169 km/h). The winds caused a major BLOWDOWN in which about 60,000 trees were damaged or destroyed in two forests on the outskirts of Paris, about 2,000 trees lining Paris streets were uprooted, and in France as a whole 160 square miles (259 km^2) of forest were destroyed. More than 120 people lost their lives.

A storm that affects only a small area is known as a local storm. THUNDERSTORMS and SQUALLS are considered to be local storms.

In a revolving storm the air moves cyclonically (*see* CYCLONE), so it rotates about a low-pressure center. Tropical cyclones are revolving storms. Revolving storms are contrasted to convectional storms that are produced by cumulonimbus clouds (*see* CLOUD TYPES) which are isolated or that form a SQUALL line.

A severe storm is any storm that damages property or endangers life. The U.S. NATIONAL WEATHER SERVICE defines a severe thunderstorm as one that produces HAIL with hailstones 0.75 inch (19 mm) or more across, or wind GUSTS of 58 MPH (93 km/h) or more, or a TORNADO, or more than one of these. A severe-storm observation is a report of a severe storm that has been positively identified. The report states the time of the observation and the location and direction of movement of the storm.

A storm beach is a linear pile of coarse material, such as pebbles, gravel, and seashells, that has been built on a beach by the action of sea storms. During the storm, waves throw the material into a heap, and in the course of many storms they form a distinct ridge or bank. The presence of such a pile of material indicates a beach that is exposed to storms.

A layer of sediment that is deposited over a surface by the action of a sea storm is called a storm bed. Shallow waves carry fine-grained material up the shore, where it is precipitated. A storm bed is sometimes called an event deposit because it is the result of a single physical event.

storm glass A storm glass is an instrument that indicates a change in the weather. It is no longer used, but was popular in the 18th and 19th centuries. It consisted of a heavy glass tube, tightly sealed to prevent air entering from outside, that contained a supersaturated mixture of chemical compounds. The precise recipe for the contents of the glass varied from one instrument to another, but most recipes were based on camphor dissolved in alcohol, with other chemicals. Crystals would form and dissolve inside the glass, the changes apparently being linked to meteorological changes other than simple changes in temperature or air pressure. If the liquid was clear, it meant the weather would be fine. Cloudy liquid meant it would rain. If crystals formed at the bottom of the glass in winter there would be frost.

Admiral FitzRoy (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) became very interested in storm glasses. He developed one based on his own chemical mixture that was attached to some versions of the FitzRoy barometer, and he explained how to interpret the patterns in it in *The Weather Book,* published in 1863.

storm surge A storm surge is a rise in sea level, accompanied by huge waves, that is produced by large storms at sea and especially by TROPICAL CYCLONES. Water sweeping inland, often for a considerable distance, causes severe flooding and in areas struck by a tropical cyclone the storm surge may cause more loss of life, injuries, and damage to property than the wind.

In the SAFFIR/SIMPSON HURRICANE SCALE, a category 1 storm produces a storm surge of 4–5 feet (1.2–1.5 m). Category 2 produces 6–8 feet (1.8–2.4 m). Category 3 produces 9–12 feet (2.7–3.7 m). Category 4 produces 13–18 feet (4.0–5.5 m). Category 5 produces a surge of more than 18 feet (5.5 m). Storm surges can be much larger than 18 feet (5.5 m), however. Hurricane Gilbert struck the Mexican coast in 1988 with a storm surge of 20 feet (6 m) that threw onto the shore a Cuban ship that had been several miles out at sea. In 1992, tropical storm Polly produced a 20-foot (6-m) surge at the port of Tianjin, China, and in December 1999, cyclone John produced one of similar size in Western Australia. Hurricane Katrina, which devastated New Orleans in 2006, generated a storm surge of 16–30 feet (5–9 m) at different points along the coast, although in this case the flooding was due to heavy rain. The rain raised the level of Lake Pontchartrain, breaching the levees protecting the city (*see* APPENDIX II: TROPICAL CYCLONES AND TROPICAL STORMS).

Three factors contribute to produce a storm surge. The first is the drop in surface air pressure at the center of the storm. A fall in pressure of 1 millibar (mb) below the mean sea-level pressure of 1,013 mb causes the sea level to rise by about 0.4 inch (1 cm). In a tropical cyclone, measuring on the Saffir/Simpson scale, the sea-level rise due to the low pressure in the eye of a category 1 storm will be about 14 inches (36 cm). In categories 2–4 it will be 14.6–20 inches (37–51cm), 20.5–28 inches (52–71 cm), 28.4–37.8 inches (72–96 cm) respectively. In category 5, the sea level will be raised by more than 37.8 inches (96 cm).

The second factor arises from waves driven by the winds. In a severe storm, spray whipped up from the sea surface turns the sea completely white and greatly reduces horizontal visibility. It looks as though the sea is boiling, and beneath the white water the waves are huge. Their size, speed, and wavelength (*see* WAVE CHARACTERISTICS) increase in proportion to the WIND SPEED, the distance over which the wind blows (the fetch), and the length of time the wind has been blowing. Waves reach their maximum size when the wind has been blowing for about 40 hours. A wind of 110 MPH (177 km/h) can raise waves 30 feet (9 m) high, and a tropical cyclone can raise waves with amplitudes up to 70 feet (21 m). This is close to the maximum size a sea wave can attain, because waves larger than this fall forward under the weight of water. While sailing through a Pacific typhoon on February 6–7, 1933, the USS *Ramapo* measured a wave that was 112 feet (34.14 m) high. This is believed to be the biggest storm wave ever recorded.

At sea, not all waves are the same size. This is because waves interfere with one another in complex ways, sometimes augmenting and sometimes diminishing them. Of 100 waves passing a fixed point, on average there will be one wave that is 6.5 times bigger than the others. If 1,000 waves pass, there is likely to be one that is eight times bigger.

Where the winds drive waves into a confined area, such as a partially landlocked sea, or into shallower water, the water level rises dramatically. Wave amplitude increases as wavelength decreases, so waves grow higher as they approach a shelving coast. Driving water into a confined area causes water throughout the entire basin to slop back and forth like water in a bathtub when a person moves a hand back and forth through it. This motion can become very large if the slopping resonates with the natural period of the sea basin, just as the waves a hand makes in a bathtub grow bigger if the waves resonate with the size of the tub.

The final component of a storm surge is the TIDE. If the raised sea level and storm-driven waves coincide with a high tide when they reach the coast, the effect of all three factors will be added. It is under these circumstances that a storm surge penetrates farthest inland and causes its greatest damage.

storm track Storms are carried by the prevailing WIND SYSTEMS in the regions where they occur. Generally, therefore, storms in middle latitudes, where the prevailing winds are from the west, tend to move from west to east. In the TROPICS the prevailing trade winds blow from the east, so storms move from east to west. Storms rarely move in straight lines, however. In North America, a major storm that develops in Alberta is likely to curve southward into Montana and North Dakota before passing to the north of Lake Superior and into Labrador. A storm originating in Colorado may travel northeast and cross the Great Lakes.

Tropical cyclones start by moving toward the west, but as they approach land they turn to the northwest in the Northern Hemisphere and southwest in the Southern Hemisphere. This track takes them toward the subtropical highs and they curve around the western boundaries of these anticyclones. They then enter the region of the midlatitude westerlies, and their track turns increasingly toward the northeast in the Northern Hemisphere and southeast in the Southern Hemisphere. As they move across cooler water, tropical cyclones weaken and finally dissipate.

Although these are the average tracks that tropical cyclones follow, individual cyclones are subject to local influences that cause them to deviate, even to the extent of traveling for a time in the opposite direction. This makes the task of forecasting their movements very difficult. The speed at which a tropical cyclone moves is determined mainly by the rate at which the warm air above the eye moves. Most travel at 10–18 MPH (16–29 km/h), but some move faster.

Strahler climate classification A climate classification that was proposed by Arthur Newell Strahler (1918–2002), professor of geomorphology at Columbia University. His classification is closely related to the Köppen classification and can be used in conjunction with it.

The Strahler classification is of the genetic type, which means it is based on the general circulation of the atmosphere and relates regional climates to the air masses and prevailing winds (*see* wind systems) that produce them. Strahler divided the climates of the world into three main types, or groups, according to the air masses that control them. These are subdivided further into 14 climatic regions, to which he later added highland climates.

His Group 1 comprises climates that are controlled by equatorial and tropical air masses. They occur in low latitudes and include: 1. wet equatorial climate; 2. trade wind littoral climate; 3. tropical desert and steppe climates; 4. west-coast desert climate; and 5. tropical wet–dry climate (*see* climate types).

Group 2 comprises middle latitude climates controlled by both tropical and polar air masses. These are: 6. humid subtropical climate; 7. marine west-coast climate; 8. Mediterranean climate; 9. middle latitude desert and steppe climates; and 10. humid continental climate.

Group 3 comprises high latitude climates controlled by polar and arctic air masses. These are: 11. continental subarctic climate; 12. marine subarctic climate; 13. tundra climate; and 14. icecap climate. Group 3 also includes highland climates.

Further Reading

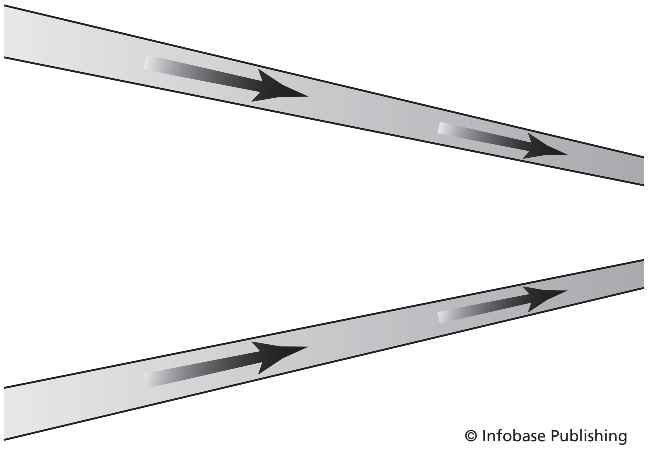
Strahler, A. N. *Introduction to Physical Geography.* New York: John Wiley & Sons, Inc., 1970.

strand line A strand line is a layer of material that was deposited at the edge of a former lake or sea and that marks the location of a shoreline that has since disappeared. Strand lines indicate higher sea levels or heavier precipitation at some time in the past, and they can therefore be used in the reconstruction of past climates.

streamline The track that is followed by moving air is called a streamline. A wind streamline is shown on a map or diagram as a straight or curved line that is parallel to the wind direction at every point along its path. The line may be drawn using information obtained from one or more synoptic charts (*see* weather maps) showing the wind that was observed and measured at particular times.

Streamlines can also be used to show the way air (or water) flows over or around an obstruction. In addition, streamline is used as a verb to describe the inclusion of a design feature in which a body, such as a car, airplane, or boat, is so shaped as to offer the least possible resistance to the flow of air or water around it. Such a shape is said to be "streamlined," because streamlines show a smooth, laminar flow of fluid around the object.

A streamline is the path traced by moving air.



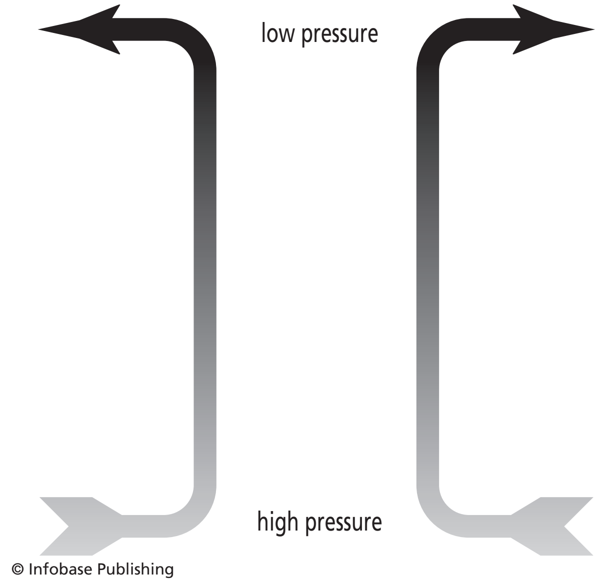
Confluence is the situation where two airstreams are approaching each other and accelerating.

The modification of a design to achieve this objective is called "streamlining."

A flow of air in which two or more streamlines approach one another is called a confluence. This accelerates the air, because a narrowing stream must carry the flow, but unlike convergence it does not lead to an accumulation of air or to any vertical movement.

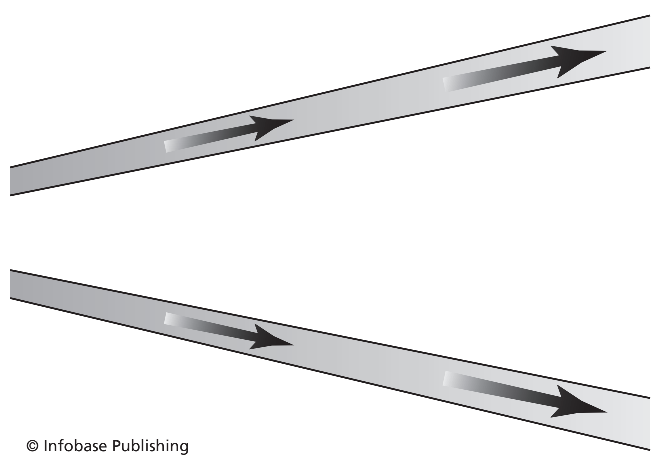
Convergence is a flow of air in which streamlines approach an area from different directions. This happens when air flows into a region of low pressure. The effect is to accumulate air where the streamlines meet. The accumulation of air increases the quantity of air in that area and, therefore, increases the atmospheric pressure. The increased pressure produced by convergence near the surface of land or sea causes air to rise, so a region of low-level convergence is also a region of rising air. The rising air eventually reaches an INVERSION level that constitutes a ceiling beyond which it can rise no farther. If the vertical motion is strong enough, air may rise all the way to the tropopause (*see* ATMOSPHERIC STRUCTURE), where air spreads out, moving away from an upper-level area that corresponds to the area of low-level convergence. This produces a region of divergence and falling pressure above the area of low-level convergence and rising pressure. A horizontal line along which convergence is occurring is called a convergence line.

Air that rises in a region of convergence cools adiabatically (*see* ADIABAT) as it does so. This favors the formation of cumuliform clouds (*see* CLOUD TYPES) and PRECIPITATION.



Convergence is the situation where air is approaching an area from several directions. This produces high pressure at the surface and low pressure above, where the air diverges.

A flow of air in which two or more streamlines move away from one another is called a diffluence. This slows the rate of flow, because there is a widening stream to carry the flow but, unlike divergence, diffluence does not result in an outflow of air from the area or to any vertical movement. A part of the atmosphere in which diffluence is occurring is called a delta region, because the diverging streamlines make a triangular shape, reminiscent of the Greek letter Δ (delta).

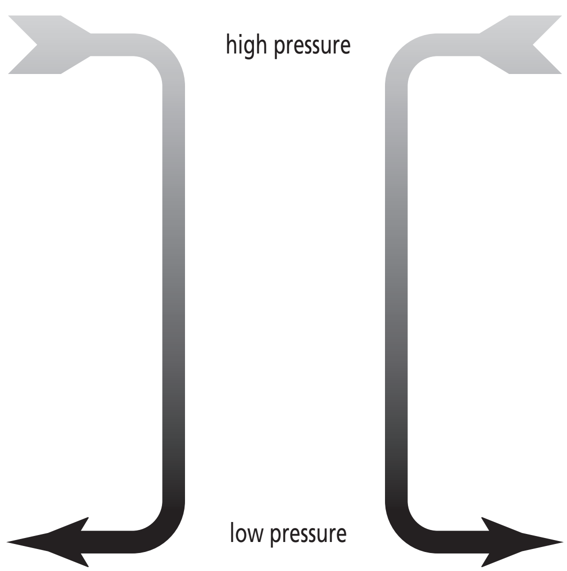


Diffluence occurs when airstreams flow away from each other and slow.

Divergence is a flow of air in which streamlines move outward from an area. This happens when air flows away from a region of high pressure. The effect is to disperse air from where the streamlines separate. Divergence decreases the quantity of air in that area and, therefore, decreases the atmospheric pressure. The decreased pressure produced by divergence near the surface of land or sea causes air at a higher level to sink and fill the low-pressure, so a region of low-level divergence is also a region of sinking air. At high level air flows inward to an area that corresponds to the area of low-level divergence. This produces a region of convergence and rising pressure above the area of low-level divergence and falling pressure. Air that sinks in a region of divergence warms adiabatically as it does so. This lowers the relative HUMIDITY of the air, favoring the dissipation of clouds and clear skies.

The horizontal movement of air when there is no FRICTION and the isobars (*see* ISO-) and streamlines coincide is called gradient flow. In this situation the tangential ACCELERATION is zero throughout the system.

A line drawn through the point of maximum curvature in the streamline of an easterly wave (*see* TROPICAL CYCLONE) is called the axis. The term is most often used in connection with equatorial waves (*see* INTERTROPICAL CONVERGENCE ZONE). The axis may be positive or negative. A positive axis indicates a TROUGH in the Northern Hemisphere and a RIDGE in the Southern Hemisphere. A negative axis indicates a RIDGE in the Northern Hemisphere and a trough in the Southern Hemisphere.



Divergence is the situation where air flows outward, producing low surface pressure.

sublimation Sublimation is the direct change of ICE into WATER VAPOR, without passing through a liquid phase. Sometimes the reverse process, in which water vapor changes directly into ice, is also called sublimation, but it is more correctly known as deposition.

The two processes can be seen happening in winter when patches of SNOW and ice disappear from the ground or when frost appears while the temperature remains well below freezing. They also occur in a freezer, when ice cubes that have been left there for too long dwindle in size and eventually disappear, and when the sides of the freezer become frosted.

The height at which ICE CRYSTALS entering dry air will change directly into water vapor by sublimation is called the ice evaporation level. Sublimation will occur if the temperature of the air is lower than -40°F (-40°C).

A snow eater is a warm, dry wind that removes snow by sublimation. A chinook wind (*see* LOCAL WINDS) often removes 6 inches (15 cm) of snow in a day and it can clear 20 inches (50 cm) in a day.

subpolar low A subpolar low is one of the two belts of low atmospheric pressure that lie between latitudes 60° and 70° in both hemispheres. They are where the polar easterly and midlatitude westerly winds converge.

The strong contrast in temperature between the tropical air arriving from one side and polar air (*see* AIR MASS) from the other gives rise to frequent DEPRESSIONS and storms. These are carried in a westerly direction by the prevailing winds (*see* WIND SYSTEMS) on the low-latitude side of the polar FRONT. The ALEUTIAN LOW and ICELANDIC LOW are the most prominent parts of the subpolar low.

subpolar region The subpolar region is the part of the world that lies between the low-latitude margin of land occupied by tundra and the high-latitude margin of lands with cool temperate or desert vegetation. Winters are long and cold, summers short, and the climate is fairly dry throughout the year. Coniferous forest is the vegetation most typical of subpolar regions.

subsidence In meteorology, subsidence is a general sinking of air over a large surface area. Subsidence brings high surface AIR PRESSURE and divergence (*see* STREAMLINE).

As air subsides, more air is drawn into the column at a high level, producing high-level convergence. Subsiding air is compressed by the increasing weight of air above it and it warms adiabatically (*see* ADIABAT).

Subsidence occurs on a global scale in the Hadley, Ferrel, and polar cells that are part of the GENERAL CIRCULATION of the atmosphere.

subtropical cyclone As the name suggests, a subtropical cyclone is a CYCLONE that occurs in the SUBTROPICS. It develops when the southern tip of a polar TROUGH in the upper atmosphere becomes cut off from the main part of the trough. The isolated pocket of low pressure, with cold air at its center, may then extend downward to the surface where it forms a very symmetrical cyclone. The center of the cyclone is up to 100 miles (160 km) in diameter, and the highest rainfall occurs about 300 miles (480 km) from the center. Subtropical cyclones are very persistent and are often absorbed into new polar troughs, rather than dissipating.

A subtropical cyclone can also develop from a TROPICAL CYCLONE that moves across land. Developing into a subtropical cyclone prolongs the rainfall from the decaying tropical cyclone. This transformation can also occur in the other direction, with a subtropical cyclone strengthening into a tropical storm. This happens if warm, moist air is drawn strongly toward the center of the subtropical cyclone. Rainfall then intensifies around the center and the temperature at the center rises until the cyclone has the warm core typical of a tropical cyclone.

Some subtropical cyclones, such as the kona cyclones of Hawaii (*see* LOCAL WEATHER), are an important source of rain.

subtropical front The subtropical front is a boundary that separates the cold water of the Southern Ocean around Antarctica from the warmer, subtropical waters farther north. The front extends from the coast of Antarctica to about 40°S. Within the front the temperature of the water rises to approximately 39°F (4°C) and the salinity increases by about 0.5 per mil, although in summer it can be as low as 33 per mil. The boundary was originally known as the subtropical convergence zone, but was renamed the subtropical front in the 1980s.

subtropical high (subtropical high-pressure belt) A subtropical high, or high-pressure belt, is one of the semipermanent ANTICYCLONES that lie in the SUBTROPICS. There are several subtropical highs, centered at about latitudes 30°N and 30°S. They are located over the ocean, are most fully developed in summer, and they strongly influence the climates to the east of them by BLOCKING or diverting DEPRESSIONS traveling from west to east in middle latitudes. The AZORES HIGH is a subtropical high that affects the climates of western Europe. The intensity of the subtropical highs varies from time to time (*see* NORTH ATLANTIC OSCILLATION). The high pressure is caused by the SUBSIDENCE of air on the descending side of the Hadley cells (*see* GENERAL CIRCULATION).

The Saharan high is the subtropical high that lies permanently over the Sahara. It is produced by the subsidence of air on the high-latitude side of the Hadley cell. The subsiding air is warm and dry, and because of the anticyclone the PRESSURE GRADIENT drives air out of the DESERT. This prevents moist air from flowing into the region and therefore maintains the arid conditions. The highest temperature ever recorded on Earth was 136°F (57.8°C) at Azizia, Libya, on September 13, 1922. Azizia lies beneath the Saharan high.

subtropics The subtropics are the two belts surrounding the Earth in both hemispheres that lie between the TROPICS and the TEMPERATE BELT. The subtropics are not sharply defined, but they are bounded by the Tropics on the side nearest the equator and by approximately latitude 35–40° on the side nearest the pole.

The latitudinal boundary represents an average, however. The actual boundary is farther from the equator on the western sides of continents and closer to the equator on the eastern sides. This difference is due to the anticyclonic (*see* ANTICYCLONE) circulation in the subtropical high-pressure belt (*see* SUBTROPICAL HIGH), which carries cooler air toward the equator on the western sides of the continents and warmer air toward the equator on the eastern sides.

sulfur cycle The pathways by which the element sulfur moves between the rocks, air, and living organisms constitute what is known as the sulfur cycle. Sulfur is an essential ingredient of proteins and protein–carbohydrate complexes, so all living organisms require it.

Fairly small amounts of sulfur enter the air from volcanic eruptions (*see* VOLCANO), but the principal sources are the WEATHERING of rocks and the oceans, both of which contribute approximately equal amounts. Whether it is released through weathering, dissolves into surface waters from the air, or is incorporated in living tissue, sulfur eventually reaches rivers that carry it to the sea. Some sulfur is deposited as a variety of compounds in the airless muds of estuaries and bogs where BACTERIA obtain energy by reducing it and releasing gases as a by-product of the chemical reactions involved. Hydrogen sulfide (H_2S) is the gas released in the largest amounts by sulfur-reducing bacteria.

In the oceans several species of phytoplankton (very small, plantlike organisms) release dimethyl sulfide (*see* CLOUD CONDENSATION NUCLEI), some of which enters the air where it is oxidized eventually to sulfate (SO_4) AEROSOL. Sulfate aerosol particles act as cloud condensation nuclei, returning sulfur to the surface.

The burning of fuels now adds significantly to the natural cycle. Depending on its quality, coal contains an average of 1–5 percent sulfur and oil contains 2–3 percent. When these fuels are burned, the sulfur enters the air as sulfur dioxide (*see* AIR POLLUTION) unless it is removed from the waste gases. Averaged over the whole world, the amount of sulfur entering the air as a consequence of burning fuel is approximately equal to the amount entering the air in the course of the natural cycle. The difference is that the burning of fuel is concentrated in the industrialized regions of the world.

Sullivan winter storm scale A five-point scale for classifying winter storms was devised in 1998 by Joe Sullivan, a meteorologist employed by the NATIONAL WEATHER SERVICE in Cheyenne, Wyoming. The Sullivan scheme ranks storms as: 1. minor inconvenience; 2. inconvenience; 3. significant inconvenience; 4. potentially life-threatening; and 5. life-threatening.

Sun The Sun is the star around which the planets of the solar system revolve, and the source of all of the light and almost all of the heat (a small amount is released from the Earth's crust) on which life depends. Astronomically the Sun is classed as a G2 V star, where G2 indicates the second-hottest class of yellow G stars, and V indicates a main-sequence or dwarf star; despite the name, the Sun is a medium-sized star, not a very small one. G stars are so designated because of the prominence of certain atoms and molecules in their spectral line; this was first observed by the German astronomer Joseph von Fraunhofer (1787–1826), who called them class G stars. V stars are typical G2 stars, with a surface temperature of about 10,960°F (5,800 K, 6,073°C).

The Sun comprises more than 99 percent of the total mass of the solar system. The mass of the Sun is 743 times that of all the planets of the solar system combined. It is 330,000 times more massive than Earth.

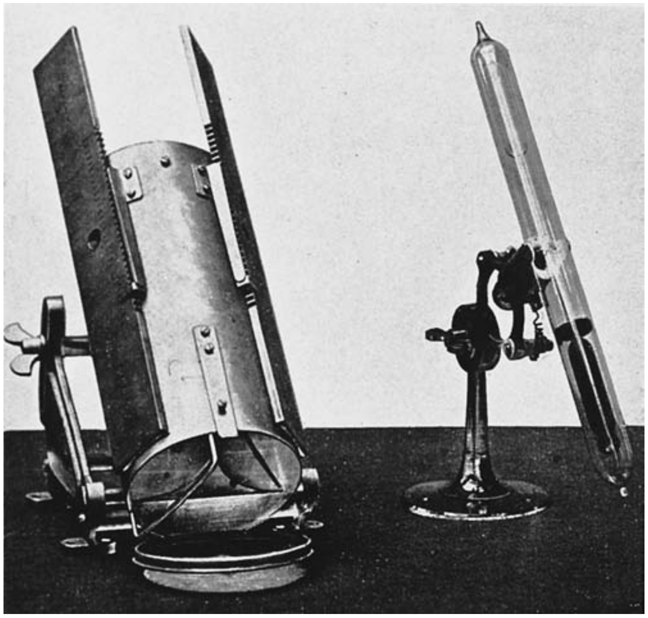
The visible surface of the Sun or any other star is called the photosphere. The Sun's photosphere is a layer of gas about 300 miles (500 km) thick that is opaque to radiation at the base but transparent at higher levels. It is the layer from which the solar radiation is emitted, and it is visible because it emits light. The temperature of the photosphere is about 10,960°F (5,800 K, 6,073°C) at the base and falls to about 7,725°F (4,000 K, 4,270°C) at the top. Above the photosphere there lies the chromosphere.

The chromosphere is the gaseous layer that lies above the photosphere. The temperature rises through the chromosphere from about 7,725°F (4,000 K, 4,270°C) at the base to about 18,525°F (10,000 K, 10,275°C) at the top. When the Sun is hidden by a solar ECLIPSE, the chromosphere appears as a pink glow, the color giving the layer its name of chromosphere, or "colored sphere."

A plage is a bright area on the chromosphere that is associated increased emission of radiation in the X-ray, extreme short-wave ULTRAVIOLET, and radio wavelengths (*see* SOLAR SPECTRUM).

sunshine recorder A sunshine recorder is an instrument that measures the intensity and duration of INSOLATION. There are several designs. The Campbell-Stokes sunshine recorder is one of the oldest and is still widely used.

The Campbell-Stokes sunshine recorder provides a daily record of the number of hours of sunshine. It comprises a spherical lens that acts as a burning glass, focusing the sunlight onto a card graduated with a timescale that partly encircles the lens. When the sky is clear, the sunshine makes a scorch mark on the card.



Two types of sunshine recorder that were replaced by the Campbell-Stokes sunshine recorder. The instrument on the left is a Jordan's sunshine recorder and the one on the right is a Marvin's sunshine recorder. The pictures are taken from "The Aims and Methods of Meteorological Work" by Cleveland Abbe, in volume I of *Maryland Weather Service,* published in 1899. *(Historic NWS Collection)*

The position of the mark on the card is determined by the position of the Sun in the sky and the graduation on the card interprets this as a time of day. The scorch mark ends whenever cloud obscures the Sun. The recorder will produce a reading for as long as the Sun is more than about 3° above the horizon.

Pyranometers (*see* SOLAR IRRADIANCE) measure solar radiation at all wavelengths (*see* WAVE CHARACTERISTICS) and over a complete hemisphere. A pair of pyranometers, one facing upward and the other downward, are used to measure surface ALBEDO. Pyrheliometers measure direct solar radiation perpendicular to a surface. Diffusographs, which are pyranometers modified by being surrounded by a shade ring, measure diffuse sunlight.

Possibly the simplest device is the actinometer, which consists of two THERMOMETERS, one with a blackened bulb. This thermometer absorbs more heat than does the thermometer with a clear-glass bulb, and the difference between the two temperatures they record can be used to calculate insolation.

sunspot A sunspot is a dark patch on the visible surface (photosphere) of the Sun, up to 31,070 miles (50,000 km) across, where the temperature is about 2,700°F (1,500°C) cooler than the surrounding area. Sunspots are caused by intense magnetic fields, which strongly affect the strength of the SOLAR WIND: the greater the number of sunspots, the more intense the solar wind.

The number of sunspots increases and decreases over an approximately 11-year cycle. This is associated with the approximately 22-year cycle, known as the Hale cycle, during which the magnetic polarity of the Sun reverses. Climate records for the last 300 years show that DROUGHTS in the western United States are most severe in the 2–5 years following one of the sunspot minima which occur every 11 years, and therefore twice in the course of the Hale cycle. The Hale cycle was discovered by the American astronomer George Ellery Hale (1868–1938). Professor Hale was also famous for developing large astronomical telescopes, including the 200-inch (508 cm) Palomar telescope and the 60- and 100-inch (152.4–225.4 cm) reflecting telescopes at the Mount Wilson Observatory, as well as for his research into solar physics.

There have been episodes in history when very few sunspots have formed. These episodes have coincided with climatic changes on Earth, the first such correlation to be recognized now being called the SPÖRER MINIMUM, although the MAUNDER MINIMUM is better known. The solar wind affects the intensity of COSMIC RADIATION reaching the Earth's atmosphere, which in turn influences cloud formation.

Sunspot activity is also linked to the intensity of ultraviolet radiation (*see* SOLAR SPECTRUM). This, through its absorption by OZONE, affects the TEMPERATURE in the upper atmosphere, which in turn affects the JET STREAM and the temperature in the lower atmosphere. Some scientists believe GLOBAL WARMING can be partly or even wholly attributed to variations in solar output indicated by changes in the number of sunspots. The regular increase and decrease in the amount of radiation that is emitted by the Sun is called the solar radiation cycle.

supercell A supercell is the type of CONVECTION cell that sometimes develops in a very massive cumulonimbus storm cloud (*see* CLOUD TYPES). A supercell storm is capable of producing TORNADOES.

Three conditions are needed for the growth of a supercell storm. There must be a warm, moist AIR MASS in which the air is conditionally unstable (*see* STABILITY OF AIR). There must also be an advancing cold FRONT to lift the warm air. Finally, there must be a strong WIND SHEAR at a high level to carry away the rising air.

Under these conditions, warm, moist air is first lifted by the cold air moving beneath it and then drawn upward by convection. The rising air cools adiabatically (*see* ADIABAT), and its WATER VAPOR condenses, releasing LATENT HEAT. The release of latent heat warms the air and increases its instability. Convergence (*see* STREAMLINE) at a low level is accompanied by divergence at high level, due to the wind shear. This accelerates the rising air. When the storm is fully developed, the upcurrents may travel at 100 MPH (160 km/h).

Supercell storms at Miami, Texas, on June 19, 1980 ***(NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory [NSSL])***

PRECIPITATION falls as HAIL, SNOW, or RAIN from the upper part of the cloud. As it falls, the precipitation chills the air around it and drags cold air to lower levels. This produces cold downcurrents. In most storm clouds the precipitation and its cold air fall into the upcurrents. They chill the rising air, and within an hour or so they suppress the upcurrents altogether. Then the cloud dies.

A supercell is different, because its upcurrents rise at an angle to the vertical. Instead of falling directly into the rising air, the precipitation falls to the side of it. Consequently, the upcurrents are not suppressed. This allows the cell to continue growing. The biggest supercell clouds break through the tropopause (*see* ATMOSPHERIC STRUCTURE) and reach heights of up to 60,000 feet (18.3 km).

A supercell is also different for another reason. In ordinary storm clouds there are usually several convection cells. These share the energy of the storm, the size of each individual cell is limited, and the cold downcurrents of one cell suppress the warm upcurrents of the adjacent cell. In a supercell storm there is only one cell. It is huge and it occupies the whole of the interior of the cloud. The resulting storm releases very heavy rainfall and hail consisting of large hailstones.

Supercell storms last for much longer than ordinary storms do, but they seldom survive for longer than about three hours. This does not mean that the storm dies after a maximum of three hours, however, because the downdraft emerging at the base of the cloud can lift more conditionally unstable air and trigger the formation of a new cloud. This is what happens in a SQUALL line, where each storm produces a new storm as it dies.

supercooling Supercooling is the chilling of water to below its freezing temperature without triggering the formation of ICE. Ordinarily, pure water freezes when its temperature falls to 32°F (0°C). If the water contains dissolved impurities, such as salt, it freezes at a slightly lower temperature. In the air, however, a cloud droplet that falls slowly through very cold air can be chilled to well below freezing temperature without freezing. It is then said to be supercooled, and clouds often contain supercooled water droplets at temperatures as low as -20°F (-29°C).

Water droplets will freeze at temperatures between about -5°F and -13°F (between -15°C and -25°C), but only if FREEZING NUCLEI are present. In the absence of freezing nuclei, water droplets have been cooled under laboratory conditions to temperatures as low as -40°F (-40°C). Below this temperature ice starts to form by homogeneous nucleation.

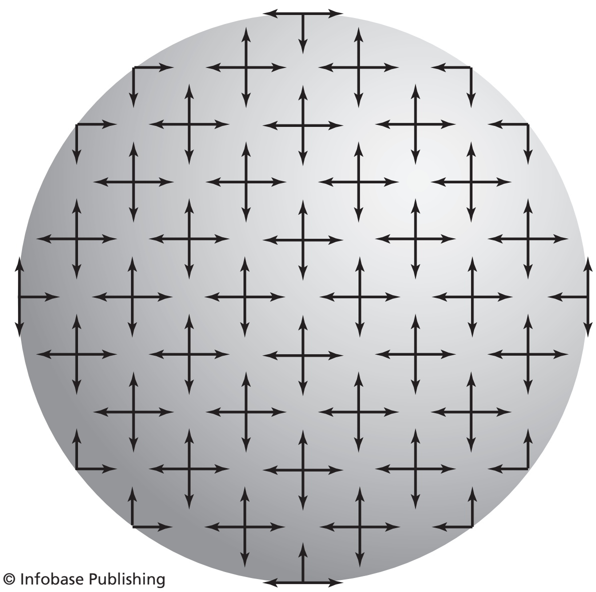
An ice nucleus is any small particle onto which supercooled water will freeze. Both freezing nuclei and sublimation nuclei (*see* DEPOSITION) are classed as ice nuclei.

surface tension Surface tension is a property of a liquid that makes it seem as though a thin, flexible skin covers its surface. The phenomenon is caused by the mutual attraction of molecules in the liquid.

Below the surface of the liquid each molecule is attracted equally in all directions. The forces acting on it are balanced and it can move in any direction. Molecules at the surface are attracted by molecules to either side and beneath them, but there are no molecules beyond the surface to balance this attraction. Consequently, surface molecules are held firmly by molecular attraction from the sides and below. This attraction draws the surface molecules into a spherical shape, in which the forces are most evenly distributed. It is surface tension that draws small volumes of liquid into drops and the surface of liquids contained in tubes or vessels into a convex shape called a meniscus.

A RAINDROP falling through the air is surrounded by air on all sides, and the water molecules are subjected only to the attraction of other molecules within the drop. A raindrop is therefore able to assume a spherical shape that is then distorted into a teardrop shape by the force of gravity. Bubbles, in which air is contained by water, are spherical because of surface tension, but ordinarily the surface tension of water is so high that they survive for only a very short time before the water molecules move toward one another to form a drop, excluding the air. This bursts the bubble. Bubbles can be made to last longer by adding detergent to the water. Detergent reduces the surface tension that causes the bubble to collapse.

A drop of liquid that is lying on a solid surface also experiences attraction to molecules in the solid material. This produces adhesion tension. If the liquid is held in a container, adhesion tension will draw it up the sides, so the surface of the liquid assumes a concave shape. CAPILLARITY is caused by adhesion tension. If the liquid is in contact with another liquid, the surfaces of both liquids generate forces of attraction. This is called interfacial tension.



Surface tension is caused by the mutual attraction of molecules at the surface of a liquid. The arrows indicate the forces acting on the molecules. Inside the liquid mass, the forces act equally in every direction. At the surface, there are no molecules to exert an attraction from the outside, so the molecules are held by forces acting to the sides and toward the center.

Surface tension (symbolized by γ) is measured in thousandths of a newton per square meter (mN/m^2, *see* APPENDIX VIII: SI UNITS AND CONVERSIONS). It decreases with increasing temperature. For water in contact with air, γ = 74.2 mN/m^2 at 50°F (10°C), 72.0 mN/m^2 at 77°F (25°C), and 62.6 mN/m^2 at 176°F (80°C).

Water has a much higher surface tension than many other liquids, but that of mercury is higher (γ = 472 mN/m^2 at 68°F, 20°C and 456 mN/m^2 at 212°F, 100°C). The alcohol used in some THERMOMETERS has γ = 23.6 mN/m^2 at 50°F (10°C) and 21.9 mN/m^2 at 86°F (30°C).

surface weather observation A surface weather observation is an observation or measurement of weather conditions made at ground level or on the surface of the sea. Surface observations have been made and recorded for many years, so they provide the longest continuous series of data. Surface data from the past are difficult to interpret, however. At one time the methods of observing, measuring, and recording were not standardized, so it is unwise to draw any conclusions from comparisons between data from different stations.

It is not safe even to compare data from the same station at different times unless the full history of the station is available. Most WEATHER STATIONS have been moved at one time or another, and a change in location of only a few yards may alter the winds, TEMPERATURES, AIR PRESSURES, and HUMIDITY to which the instruments are exposed. A station may remain in the same place, but its surroundings may change. Urban developments may envelop it, but the change may be subtler than that. The closure of a factory upwind or the installation of equipment to remove pollutants from its chimney emissions may alter the temperature of the air or intensity of INSOLATION at the weather station. Even the removal of trees can affect wind patterns.

It is impossible to correct for all these influences and dangerous to assume that they will tend to cancel one another because for any factor an increase in one place is compensated by a decrease somewhere else. Surface weather observations made today under standard conditions are essential for the compilation of synoptic charts (*see* WEATHER MAPS) and the preparation of weather forecasts. They can also be used, with caution, to detect climatic changes over recent years, but they provide an unreliable base for estimates of climatic change since earlier times.

synoptic An adjective that is derived from the Greek word *sunoptikos,* from *sun,* meaning "with," and *optikos,* which means "seen." Synoptic refers to something that is based on a general view of conditions over a large area at a particular time. In synoptic METEOROLOGY, data gathered from many places is assembled to provide a picture of atmospheric conditions over a large area.

Conditions that are seen to cover an area that is large, but not so large as in the picture presented in a synoptic view, are said to be subsynoptic. Satellite images of cloud patterns over the ocean are subsynoptic in extent. They are able to show features the size of a TROPICAL CYCLONE in an area that is approximately 1,000 miles (1,600 km) square, but a synoptic chart (*see* WEATHER MAP) would cover a much bigger area.

T

Tay Bridge disaster The Tay Bridge disaster was a devastating catastrophe that occurred in the 19th century on the rail bridge that crosses the Firth of Tay, Scotland, linking Fife to the city of Dundee on the northern side of the river. The present bridge is the second (and a road bridge also spans the Firth).

The first Tay Bridge was opened on June 20, 1877. It was rather more than 1 mile (1.6 km) long, and the engineers who designed it believed it was strong enough to withstand any weather. On the evening of Sunday, December 28, 1879, a train departed as usual from Edinburgh with six carriages carrying passengers bound for Dundee. There were between 75 and 90 persons on the train as it began to cross the Tay Bridge. The weather was stormy, with gale-force winds blowing at up to 75 MPH (120 km/h). At about 7.15 P.M., when the train was about halfway across, the bridge collapsed and the entire train fell into the river below. There were no survivors. The subsequent investigation concluded that the bridge had not been properly built and maintained and that its design failed to allow adequately for wind loading. Some scientists now believe it was destroyed when two TORNADOES struck it simultaneously.

Further Reading

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Martin, Tom. "The Tay Bridge Disaster." Available online. URL: www.tts1.demon.co.uk/tay.html. Accessed February 15, 2006.

teleconnections Linked atmospheric changes that occur in widely separated parts of the world are known as teleconnections. The SOUTHERN OSCILLATION index is a typical example. When the sea-level atmospheric pressure rises above normal at Darwin, Australia, it falls by an approximately similar amount at Tahiti, in the central South Pacific, thousands of miles away. El Niño (*see* ENSO) brings dry weather to northeastern Brazil and also to the western Mediterranean, the Sahel region of Africa, northeastern China, and Australia, but wet weather to much of the United States, Israel, and northwestern Europe.

There are many other examples. Changes in the water temperature of the tropical eastern North Pacific Ocean are linked to changes in AIR PRESSURE in the upper atmosphere over the Rocky Mountains. The water temperature in the center of the tropical North Pacific Ocean is linked to the temperature of the water in the Indian Ocean. The rainfall in northeastern Brazil is linked to the sea-surface temperature in the eastern tropical South Pacific Ocean.

telegraphy The transmission of information by means of electric pulses that travel along a wire cable from a sender to a receiver is called telegraphy. The word is derived from two Greek words, *tele,* which means "far," and *graphein,* which means "to write."

Until the invention of telegraphy, information could be communicated over a long distance no faster than a horse could gallop. Weather forecasting was impossible, because it took so long to assemble detailed information about conditions over a sufficiently large area that by the time the data had been analyzed the weather system the data described had disappeared.

Scientists knew by the middle of the 18th century that an electric current would travel a considerable distance along a metal wire if the wire were connected to the earth to complete the circuit. The first practical idea for a telegraph was suggested in 1753, in an article in the *Scots Magazine* by someone identified only as "C.M." C.M. proposed a separate insulated wire for each letter of the alphabet. At the receiving end, each wire was to be attached to a ball that hung above a piece of paper with a letter written on it. When the current reached the ball, the paper would jump up to it, and so the message could be spelled out letter by letter. Alternatively, each wire could end at a bell that would be struck by a ball when a current traveled along the wire. Various other inventors suggested similar systems and some of them were tried out.

These early methods were too slow and cumbersome to be practical, however. A breakthrough came in 1819, when the Danish physicist Hans Christian Oersted (1777–1851) discovered that an electric current produces a magnetic field. Other scientists, including André-Marie Ampère (1775–1836) and Pierre Laplace (1749–1827; *see* APPENDIX I: BIOGRAPHICAL ENTRIES), developed this idea and in 1825 the English inventor William Sturgeon (1783–1850) enclosed a needle within a coil of wire. The needle became a magnet when a current passed through the wire, and its polarity changed when the current changed direction. Sturgeon called his device an "electromagnet."

In 1831, Joseph Henry (1797–1878; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) made a signaling apparatus that used an electromagnet. It consisted of a magnetized steel bar that was pivoted in a horizontal position and could be attracted by an electromagnet. When the bar was drawn toward the magnet, the end of it struck a bell. Messages could thus be conveyed by a sequence of sounds. In 1835, Henry invented the relay. This was a series of similar circuits in which each circuit activated the next. It overcame the diminution in the signal passing through a length of wire that is caused by resistance in the wire itself. Samuel Morse (1791–1872; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) devised a code suitable for telegraphic use, and the MORSE CODE is still used today.

The first telegraph line in the world linked Baltimore and Washington and was opened in 1844. The first message, sent in Morse code, was "What hath God wrought?" Telegraph lines were soon being installed in many countries and also between them. The first submarine cable was laid in 1850 to link England and France. An attempt to lay a transatlantic cable was made in 1857, but the cable broke and the project had to be abandoned. The first successful transatlantic cable was laid in 1866.

Joseph Henry had been elected secretary of the Smithsonian Institution in 1846, and he used his position to establish a network of weather observers throughout the United States. The network became operational in 1849, and the observers used the telegraph to send data to the Smithsonian. This system formed the basis on which the United States Weather Bureau was formed in 1891. The first national network of meteorological stations linked to a central point by telegraph opened in France in 1863.

Further Reading

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Television and Infrared Observation Satellite (TIROS) TIROS was the world's first weather satellite, launched by the United States on April 1, 1960. By 1965, nine more TIROS satellites had been launched, several of them into polar ORBIT rather than equatorial orbits.

TIROS-8 carried the first automatic picture transmission equipment. The first Advanced Very High Resolution Radiometer was carried on *TIROS-N,* launched in October 1978. *See* SATELLITE INSTRUMENTS.

TIROS satellites are now known as NOAA-class satellites. These satellites travel in polar orbits, scanning the entire surface of the Earth over a 24-hour period. Their instruments are sensitive to visible light and infrared radiation, and they scan to the sides of the orbital path, covering an area 1,864 miles (3,000 km) wide and 1.2 miles (2 km) high. At one time, for example, they would be able to observe the entire area from southern Florida to Hudson Bay and from the Atlantic to the Great Lakes. They transmit a constant stream of data by automatic picture transmission or high-resolution picture transmission. As well as monitoring the weather, the satellites carry search and rescue transponders that are used to help locate ships and aircraft in distress.

temperate belt The region that lies approximately between latitudes 25° and 50° in both hemispheres. The lower latitude is close to the TROPICS, and the higher latitude is about at the 50°F (10°C) isotherm (*see* ISO-) of mean SEA-SURFACE TEMPERATURE.

The temperate belt lies in the middle latitudes, and its climates are often described as middle latitude (or midlatitude). The climates of the temperate belt correspond to category C in the KÖPPEN CLIMATE CLASSIFICATION, with temperatures in the coldest month between 26.6°F (-3°C) and 64.4°F (18°C) and in the warmest month temperatures higher than 50°F (10°C).

temperature Temperature is a measure of the relative warmth of an object or substance that allows it to be compared to another object or substance (one is warmer or cooler than the other) or to a standard (so many degrees). Temperature and heat are not the same thing; heat is a form of energy, temperature the effect that energy produces.

All objects and substances, including the air and our own bodies, are made from atoms and molecules. Atoms and molecules move. If they are in the form of a gas, they move freely and rapidly. Molecules in a liquid move more slowly and have less freedom. In a solid the molecules are unable to move around, but they vibrate. How fast the atoms or molecules move or vibrate depends on the amount of energy they possess. Their KINETIC ENERGY (energy of motion) can increase or decrease.

Energy cannot be created or destroyed, but one form of energy can be converted into another (*see* THERMODYNAMICS, LAWS OF). When an atom or molecule absorbs heat (one form of energy), that heat is converted to kinetic energy (another form of energy).

The kinetic energy possessed by the atoms or molecules composing an object or substance is measured as motion in relation to the center of mass of the object or substance. When moving or vibrating atoms or molecules strike another object, a proportion of their kinetic energy is transferred to that object. An appropriate sensor can detect this transferred energy. Nerve endings in our skin are sensors that detect the impact of fast-moving or vibrating atoms and molecules. The message that the nerves send to the brain is interpreted as temperature. We feel that something is hot or cold, either in relation to our own skin temperature or in an absolute sense if the skin is exposed to a temperature so high it will burn or so cold it will freeze the tissues.

A THERMOMETER is an instrument that absorbs kinetic energy from impacting atoms and molecules and converts it to a reading against a scale. There are several TEMPERATURE SCALES, but only three are widely used. Scientists usually prefer the Kelvin scale, in which the temperature is written in the unit K (for kelvin), without a degree sign. The Celsius temperature scale is the most widely used everyday scale. Sometimes still called the centigrade scale (the Latin *centum* means "hundred"), because there are 100 of its degrees between the freezing and boiling points of water, Celsius temperatures are written as °C. Its name was officially changed from centigrade to Celsius in 1948, at the Ninth General Conference on Weights and Measures. The Fahrenheit temperature scale is more often used in the United States and Britain (where it is being replaced by the Celsius scale). Its temperatures are written as °F. A fourth scale, the Réaumur, is used in very few places today.

There are several ways to report the temperature. The mean temperature is the air temperature measured at a particular place over a specified period, such as a day, month, or year, and then converted to a MEAN. Mean temperatures can also be shown, and plotted as isotherms (*see* ISO-), for large regions, continents, and for the whole world. The rate of temperature change over a horizontal distance is known as the temperature gradient.

The temperature range is the difference between the highest and lowest mean temperatures that have been recorded for a particular place. If the annual range is required, only daytime temperatures should be used. The DIURNAL range compares the mean daytime and mean nighttime temperatures for a month, season, or year. The mean range uses only mean temperatures, but the absolute range takes account of the highest and lowest temperatures ever recorded by day or night. Chicago, for example, has a mean annual temperature range of 49°F (27°C), but an absolute temperature range (measured over 75 years) of 128°F (71°C). A temperature belt is the area that lies between two lines on a graph that show the daily maximum and minimum temperatures for a particular place. The belt indicates the temperature range for that place.

Obviously, the air temperature is not everywhere the same even within a small area. Consequently, where it is measured makes a difference. Temperature is often reported as the shade temperature. This is the air temperature that is measured inside a STEVENSON SCREEN or other shelter, or anywhere out of direct sunlight. Air is heated almost entirely by contact with the ground and not by directly absorbing solar radiation. The glass of a thermometer, on the other hand, will absorb solar radiation directly, and this heat will be transferred to the liquid, raising its temperature to a level higher than that of the surrounding air. The thermometer will then give a false reading. For this reason, reported temperatures are always shade temperatures unless it is stated otherwise.

The concrete minimum temperature is the lowest temperature that is registered by a minimum thermometer that remains in contact with a concrete surface for a specified period. It is used as an alternative to the grass minimum temperature, because it gives more uniform results and provides a better indication of the likelihood of ice forming on road surfaces.

The grass minimum temperature, also called the grass temperature, is the temperature that is registered by a minimum thermometer set in the open with its bulb at the level of the tops of the blades of grass in short turf. This is the temperature to which crop plants are exposed, and it is therefore of relevance to farmers and horticulturists.

The surface temperature is the temperature of the air or sea measured close to the surface of land or water (*see* SEA-SURFACE TEMPERATURE).

The dry-bulb temperature is the temperature that is registered by a thermometer with a bulb that is dry and directly exposed to the air. A dry-bulb thermometer is used to measure the air temperature. This reading is compared with the wet-bulb temperature to determine the relative HUMIDITY and DEW point temperature. A wet-bulb thermometer registers the wet-bulb temperature. In saturated air (relative humidity 100 percent) the wet-bulb temperature will be equal to the dry-bulb temperature, indicating that no evaporation is taking place. At any relative humidity below SATURATION the wet-bulb temperature is lower than the dry-bulb temperature.

temperature scales Measuring the temperature of the air is simple enough for anyone possessing a THERMOMETER, but as scientists of past centuries explored the causes of weather phenomena, devising a thermometer that would give an accurate reading proved extremely difficult. Many scientists worked at the problem. By itself, however, a reliable thermometer is not enough. All it will show is the level of a liquid rising or falling inside a tube or a needle moving on a dial. This will indicate whether the temperature at one time is higher or lower than it was at another time, but it will not allow the difference to be quantified. Quantification calls for a recognized scale that can be used to calibrate the thermometer. Over the centuries several temperature scales have been proposed.

The Römer temperature scale was possibly the first. It was devised in about 1701 by the Danish astronomer, physicist, and instrument maker Ole Christensen Römer (1644–1710; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). Römer, also spelled Rømer, never published a description of the method he used, but in 1708 Daniel Fahrenheit visited him, watched him at work, and wrote his own account.

In 1701, Isaac Newton (1642–1727) pointed out that any temperature scale must be calibrated between two fixed, or fiducial, points. Newton suggested that average body temperature and the temperature of freezing water should be used as the two fiducial points, but Römer used the freezing and boiling temperatures of water.

According to Fahrenheit, Römer inserted his thermometer, filled with alcohol (in fact, wine), into freezing water and marked the point reached by the alcohol in the thermometer. He then placed the thermometer into tepid water, which Fahrenheit wrote was at blood heat (*blutwarm*). He then added half of the distance between these points below the lower fiducial point and marked this lowest point as 0. There is some confusion about the lower fiducial point, however. Some historians hold that Römer used a mixture of WATER, ICE, and ammonium chloride to determine the lower fiducial point and called that 0, others that he used melting snow only and called that point 7½. In either case, on the Römer scale water freezes at 7½°Rø, boils at 60°Rø, and average body temperature is 22½°Rø. The scale is no longer used, but it is important historically, because it is the one on which Fahrenheit based his scale.

Daniel Fahrenheit (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) devised his temperature scale in about 1714. It remains in use in Britain, the United States, and other English-speaking countries, although the Celsius temperature scale is steadily taking its place. Scientific publications always use either the Celsius scale or the Kelvin scale.

Fahrenheit derived his scale from the Römer temperature scale, in which two fiducial points are used, the freezing and boiling points of water. Fahrenheit modified the Römer scale by using body temperature for his upper fiducial point, and for his lower fiducial point he used the freezing point of a mixture of ice and salt. This was then believed to be the lowest temperature that could be attained, so by calling it 0° all temperature values would be positive. He marked this point on his mercury-filled thermometer and then measured body temperature. In order to be able to measure small temperature differences, Fahrenheit divided the distance between the upper and lower fiducial points into 90 degrees. On this scale the freezing point of pure water was 30° and body temperature was 90°.

Later Fahrenheit adjusted the scale. He substituted the boiling point of pure water for the upper fiducial point and divided the distance between the new upper point and the freezing point of pure water into 180 degrees, while still retaining the lower fiducial point. On the revised scale, pure water freezes at 32° and boils at 212°, and average body temperature was 96°, which was later adjusted to 98.6°.

1°F = 0.56°C; 1°C = 1.8°F. To convert Fahrenheit temperatures into Celsius, °F = (°C × 1.8) + 32; °C = (°F - 32) × 5 ÷ 9.

In 1730, the French physicist and naturalist René-Antoine Ferchault de Réaumur (1683–1757; *see* Appendix I: Biographical Entries) devised another scale. Réaumur measured the expansion of a mixture of water and alcohol as its temperature increased. The liquid was held in a bulb at the base of a tube, just like any thermometer. When it was at the freezing point, he marked the point it reached on the tube as zero. He then graduated the remainder of the tube into units, each of which was equal to one-thousandth of the volume of the liquid in the bulb and tube when it was at freezing. When the liquid reached boiling point, he found its length had increased to 1,080 units, so it had risen 80 units (or degrees). Consequently, his Réaumur temperature scale ran from 0°R at freezing to 80°R at boiling point.

In 1742, the Swedish astronomer Anders Celsius (*see* Appendix I: Biographical Entries) published a paper called "Observations on two persistent degrees on a thermometer" in the *Annals of the Royal Swedish Academy of Science*. Celsius proposed that the two fixed points should be the temperature of melting snow or ice and the temperature of boiling water, and he described his reasons for choosing these two points. Obviously, water freezes and thaws at the same temperature, but it is more difficult to measure the point at which liquid water begins to freeze than it is to measure the temperature at which snow and ice melt. Celsius reported that he had used one of the thermometers made by Réaumur to measure the temperature of melting snow. He repeated the measurement many times in the course of two winters and during all kinds of weather and at different atmospheric pressures. He even brought snow from outdoors and placed it in front of the fire in his room to measure its temperature as it melted. The temperature was invariably the same. Snow also melted at the same temperature in Paris and in Sweden at Uppsala (60°N) and Torneå (66°N). He was confident, therefore, in the first of his fixed points.

Measuring the temperature of boiling water was more complicated. Although the temperature of water will rise no further once it is boiling, Celsius thought the intensity of boiling might affect the thermometer, and he noticed that when he removed the thermometer from the boiling water the mercury rose before it began to fall. This, he suggested, was because the glass tube contracted before the mercury began to cool. Daniel Fahrenheit had observed that the boiling temperature of water varies according to the atmospheric pressure. Celsius confirmed this, but found a way to correlate the two, because the height of the mercury in the thermometer was always proportional to the height of the mercury in the nearby barometer.

Celsius then proposed a standard method for calibrating a thermometer. First the bulb of the thermometer should be placed in thawing snow and the position of the mercury marked. Then the thermometer bulb should be placed into boiling water when the atmospheric pressure is approximately 1,006.58 millibars (29.75 inches or 755 mm of mercury). The position of the mercury should be marked.

The distance between the two points should then be divided into 100 equal parts, or degrees, so that 0 degree corresponds to the boiling temperature of water and 100 degrees corresponds to its freezing temperature.

This was the Celsius scale. It was later reversed, so that 0 degree represents the freezing temperature of water and 100 degrees the boiling point. It is uncertain who made the change. It may have been Martin Strömer, a pupil of Celsius. It has also been suggested that it was Carl von Linné (Linnaeus). The most likely person, however, was the leading Swedish instrument maker of the time, Daniel Ekström.

The Celsius temperature scale is the one that is used throughout most of the world. In English-speaking countries the Fahrenheit temperature scale is also used, although not for scientific measurements, where the Celsius scale is preferred.

Because there are 100 degrees, the scale is sometimes called the centigrade scale, from the Latin *centum,* meaning "hundred," and *gradus,* meaning "step." The name was officially changed from centigrade to Celsius in 1948, at the Ninth General Conference on Weights and Measures.

The Kelvin scale is the one most often used in scientific publications, and the kelvin is the unit of temperature in the SI scheme (*see* Appendix VIII: SI Units and Conversions). The scale was devised by William Thomson (1824–1907), who later became Lord Kelvin. He called it the "absolute" scale. One kelvin, written as 1 K with no degree sign (not as 0°K), is equal to 1°C (1.8°F), and 0 K, or absolute zero, is equal to –273.15°C (-459.67°F).

The Rankine scale is sometimes used as an alternative to the Kelvin scale, mainly in the United States. It is used, for example, in calculating density altitude (*see* density), but its main use is in engineering. The scale was devised by the Scottish engineer and physicist William John Macquorn Rankine (1820–72). The Rankine degree (R) is equal to a Fahrenheit degree, but the Rankine scale extends to absolute zero. 0°R = –459.67°F. Water freezes at 492°R and boils at 672°R. The advantage of the Rankine scale is its compatibility with the Fahrenheit scale. Fahrenheit temperatures can be converted to Rankine temperatures without first having to convert the degrees themselves.

Absolute temperature is the temperature measured on the Kelvin scale, which has no negative values. To convert a Fahrenheit temperature to the equivalent absolute temperature, K = ((°F - 32) × 5 ÷ 9)) + 273.15. The absolute temperature at which water freezes (32°F) is 273.15 K and the temperature at which it boils (212°F) is 373.15 K. Absolute zero, or zero on the absolute (Kelvin) scale, is the temperature at which the kinetic energy of atoms and molecules is at a minimum. It is the lowest temperature possible (and unattainable according to the third law of thermodynamics; *see* thermodynamics, laws of). The existence of absolute zero was first implied in the work of Jacques Charles (*see* Appendix I: Biographical Entries and gas laws). Absolute zero (0 K) is equal to -459.67°F (-273.15°C).

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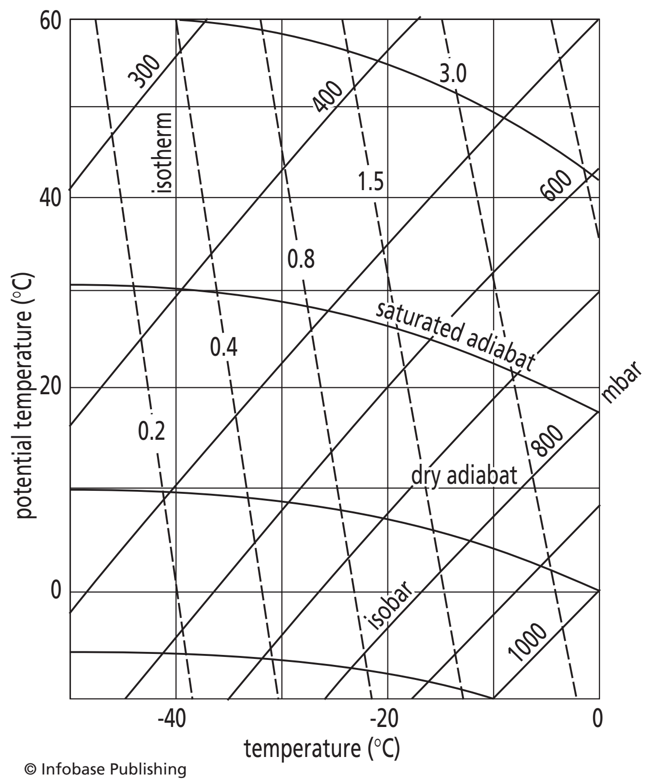
tephigram **(TΦgram)** A tephigram is a thermodynamic diagram on which the temperature and humidity of the air are plotted against air pressure. This reveals the entire structure of a column of air.



A tephigram is a graph on which temperature and humidity are plotted against pressure to illustrate the structure of an entire column of air. The actual temperature is plotted against the horizontal axis, the logarithm of the potential temperature against the vertical axis, pressure by the solid diagonals, and saturation specific humidity by the broken lines.

The actual temperature is plotted against one axis and the logarithm of the POTENTIAL TEMPERATURE against the other. Vertical lines then represent isotherms (*see* ISO-) and horizontal lines are isotherms of potential temperature. The horizontal lines are also dry ADIABATS and the distance between them decreases as the potential temperature increases.

Saturated adiabats appear as curved lines. In the lower troposphere (*see* ATMOSPHERIC STRUCTURE), the saturated adiabats cross the dry adiabats at about 45°, but the angle becomes smaller with increasing altitude. Isobars (*see* ISO-) are slightly curved lines running diagonally across the diagram from lower left to upper right and almost bisecting the right angles at which the isotherms intersect. Isopleths, showing the saturation specific humidity, are shown as dotted lines that make a small angle with the vertical isotherms.

When the tephigram has been constructed, it is sometimes rotated clockwise by about 45° so that the isobars lie horizontally. These then correspond to altitude and can be labeled as such, in addition to being labeled in units of pressure (usually millibars). The conventional symbol for potential temperature is the Greek letter phi (Φ), so the tephigram is a t (for temperature) phi (for potential temperature) -gram. The tephigram was devised by Sir Napier Shaw (*see* APPENDIX I: BIOGRAPHICAL ENTRIES).

terminal velocity Terminal velocity is the maximum speed that a falling body can attain. Once the body has accelerated to its terminal velocity, it continues its descent at that constant speed. The terminal velocity of a body is therefore proportional to its weight and to the drag exerted on it as a result of the resistance to its passage offered by the medium through which it is falling. That drag is proportional to the surface area of the body, because this is the surface against which resistance acts, and the weight is proportional to its volume.

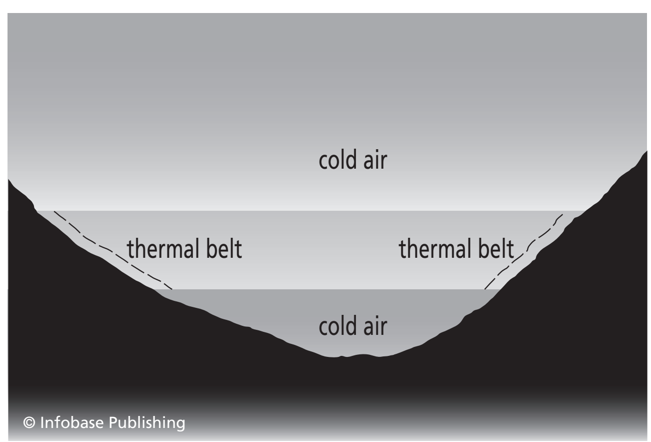
If the body is very small, the flow of air around it is dominated by the VISCOSITY of the air. For larger bodies, the downward force acting on the body is equal to the weight of the body minus the weight of the air it displaces. In the lower troposphere (*see* ATMOSPHERIC STRUCTURE), the terminal velocity (V) of a falling body the size of a small raindrop is given by $V = 8 \times 10^3 r$, where r is the radius of the body. The airflow around large raindrops and hailstones is much more turbulent, and their terminal velocity is given by $V = 250r^{1/2}$. *See also* STOKES'S LAW.

The speed with which a body, such as a RAINDROP, SNOWFLAKE, or hailstone, falls through the air is called its fall speed. This is equal to the terminal velocity of the body minus the velocity of any upward air current to which it is exposed.

Tertiary The sub-era of the CENOZOIC era of geologic time (*see* APPENDIX V: GEOLOGIC TIMESCALE) that began 65.5 million years ago and ended 1.81 million years ago. The Tertiary includes the PALEOGENE and NEOGENE periods.

The name Tertiary was introduced in 1758 by Giovanni Arduino (1714–95), a professor at the University of Padua, Italy. Arduino divided the rock strata of the Apennine Mountains of central Italy into three, calling them Primary, Secondary, and Tertiary. The names Primary and Secondary were abandoned long ago, and Tertiary has now been abandoned for formal use.

thermal belt A thermal belt is a fairly well defined area on many mountainsides in middle latitudes where nighttime temperatures are higher than the temperatures at higher and lower elevations. Below the thermal belt cold air subsides katabatically at night to produce low temperatures and often a FROST hollow in the valley bottom. Above the thermal belt the adiabatic (*see* ADIABAT) decrease in temperature with height also produces cold air.



The thermal belt is a region on a mountainside where the nighttime temperature is higher than it is at higher or lower elevations.

thermal equator The belt around the Earth where the temperature is highest is called the thermal equator. Its location changes with the SEASONS between 23°N and between 10°S and 15°S. The mean location of the thermal equator is about 5°N.

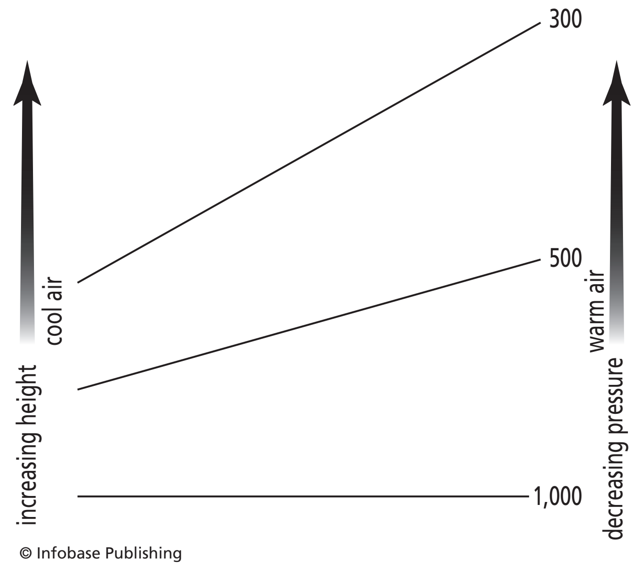
The thermal equator is not the same as the meteorological equator, although both occupy the same position. The meteorological equator is the mean latitude of the equatorial trough (*see* INTERTROPICAL CONVERGENCE ZONE), which is also 5°N.

thermal wind A thermal wind is generated when the air temperature changes by a large amount over a short horizontal distance. The JET STREAM and the easterly jet are the most important examples.

Warm air is less dense than cool air. Where warm and cool air lie adjacent to each other, therefore, AIR PRESSURE decreases with height more rapidly in the cool air than in the warm air, because the cool air is the more compressed. Consequently, a CONSTANT-PRESSURE SURFACE (a surface across which the atmospheric pressure is the same everywhere) slopes upward from the cool, dense air to the warm, less dense air, and the THICKNESS of each atmospheric layer increases along a gradient from the dense air to the less dense air. This gradient becomes steeper with increasing height, because the thickness of a layer depends on the degree to which the air is compressed, and compression decreases with height more slowly in dense air than in air that is less dense.

The speed of the GEOSTROPHIC WIND is proportional to the PRESSURE GRADIENT or, to put it another way, to the slope of the constant-pressure (or isobaric) surface. This means that if the slope angle of the isobaric surface changes with height, so must the speed of the geostrophic wind. The thickness of a layer that is bounded by two isobaric surfaces is proportional to the mean temperature in the layer. It therefore follows that the change in the speed of the geostrophic wind across the layer is proportional to the temperature gradient across the layer. This means the layer must be BAROCLINIC. The relationship between the geostrophic WIND SHEAR and baroclinicity is known as the thermal wind relation.

Since the temperature gradient increases with height, so does the wind speed. It blows with the cool air to its left in the Northern Hemisphere and to its right in the Southern Hemisphere, which is why the polar FRONT and subtropical jet streams blow from west to east in both hemispheres.



Pressure decreases with height more rapidly in cool, dense air than it does in warm air, which is less dense, and the thickness of each layer defined by pressure is proportional to the temperature. Where warm and cool air lie adjacent to each other, this produces a temperature gradient that increases with height. It is the gradient that generates the thermal wind.

The movement of an atmospheric disturbance in the direction the nearest thermal wind is blowing is called thermal steering. The thickness of the layer used to calculate the thermal wind is usually taken to extend from the surface to the middle troposphere (*see* ATMOSPHERIC STRUCTURE) and thermal steering is equivalent to movement along THICKNESS lines.

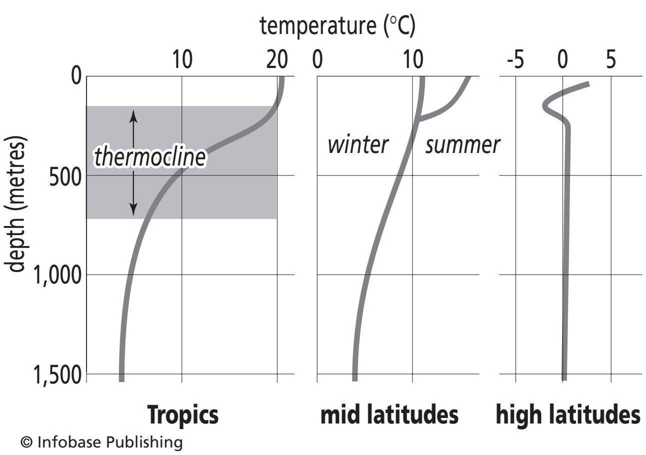
thermocline Literally, a thermocline is a change of temperature that occurs along a gradient between two places. More specifically, the thermocline is a layer in the ocean where the temperature decreases with depth much more rapidly than it does in the water above or below. The depth of the thermocline varies from place to place and with the seasons, but it may commence as little as 33 feet (10 m) or as much as 660 feet (200 m) below the surface and end at depths between 500 feet (150 m) and 5,000 feet (1,500 m). In Arctic and Antarctic waters there is usually no thermocline, because the sea surface is covered by ice during the winter and there is only slight warming by solar radiation in summer. The strongest thermocline is found in the TROPICS.

Water at the ocean surface is warmed by solar radiation. In the Tropics, the SEA-SURFACE TEMPERATURE commonly exceeds 68°F (20°C) and can reach 80°F (27°C). This is probably a maximum because the rate of evaporation increases with temperature to a point at which the LATENT HEAT of vaporization cools the surface layer sufficiently to prevent the temperature rising any higher. Radiant heat does not penetrate very deeply, and the ocean loses heat to the atmosphere by long-wave radiation, but winds and currents mix the upper waters, and it is this mixing that carries warm water to a greater depth. Mixing also helps constrain the sea-surface temperature.

At about 13,000 feet (4,000 m), which is the average depth of all the oceans, the water temperature is between 34°F and 36°F (1°C–2°C). This temperature remains constant throughout the year, regardless of latitude. The deep ocean is the most unchanging environment on Earth.

Mixing produces an upper layer of water in which the temperature decreases only very slightly with depth. Below the mixed layer, water temperature begins to decrease sharply with depth, and by about 3,300 feet (1,000 m) it has fallen to approximately 40°F (4.4°C). From there it decreases much more gradually.

The thermocline is the layer in which temperature decreases rapidly, and it is most strongly marked in the Tropics because there the temperature must fall from about 68°F (20°C) to about 40°F (4.4°C). In midlatitudes, where the water in the mixed layer is cooler, the temperature gradient is shallower, especially in winter when the surface temperature is about 54°F (12°C). In summer, when the sea is warmer, there is a more sharply defined summer thermocline very close to the surface. In latitudes higher than about 50°N and 50°S, there is no thermocline.



The thermocline is the ocean layer in which temperature decreases most rapidly with depth. The tropical thermocline is of much greater vertical extent than the high-latitude thermocline. In midlatitudes, the thermocline almost disappears in winter.

Solar radiation is absorbed by the oceans, but it warms only the water above the thermocline. When warmed, the oceans warm the air in contact with them. Cooler water from the thermocline that becomes incorporated into the mixed layer is immediately replaced by cold water from a higher latitude. It is partly through this coupling of oceans and atmosphere that heat is transferred by ADVECTION from low to high latitudes. A thermocline also develops in many lakes in summer.

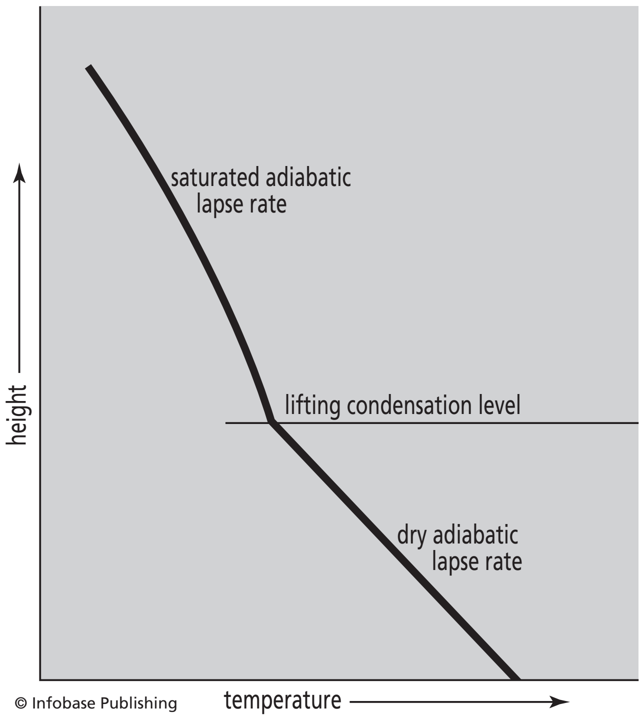
thermodynamic diagram A thermodynamic diagram summarizes the factors affecting the temperature and pressure of a PARCEL OF AIR. A point on the diagram then refers to the thermodynamic (energy) state of the air in that location.

A simple thermodynamic diagram measures altitude along its vertical axis, and temperature along its horizontal axis. A line showing the change of air temperature with height corresponds to the LAPSE RATE and indicates the height of the lifting condensation level, marking the boundary between the dry and saturated adiabatic lapse rates (*see* ADIABAT) and the height of the CLOUD BASE. The most widely used types of thermodynamic diagram are the Stüve chart and TEPHIGRAM.

A line drawn on a thermodynamic diagram to show the lapse rate of air that is rising past the lifting condensation level is called a pseudoadiabat. The pseudoadiabatic lapse rate is almost the same as the saturated adiabatic lapse rate.

A Stüve chart, also called an adiabatic chart or pseudoadiabatic chart, is a thermodynamic diagram in which temperature is plotted along the horizontal axis and pressure along the vertical axis, with the highest pressure at the bottom. Pressure is calculated as the AIR PRESSURE raised to the power of 0.286. The chart was devised by G. Stüve and has been widely used, although meteorologists now find the tephigram more useful.

An aerological diagram is a thermodynamic diagram on which data from soundings of the upper atmosphere are plotted. The diagram usually shows isobars (*see* ISO-), isotherms (lines joining points at equal temperatures), and dry and saturated adiabats.



A thermodynamic diagram illustrates the amount of energy a parcel of air possesses. In this example, temperature is plotted against height to show the lapse rate. The lifting condensation level marks the height at which the dry and saturated adiabatic lapse rates meet.

thermodynamics, laws of Thermodynamics is the scientific study of the ways in which energy changes from one form into another, the way it is transmitted from one place to another, and its availability to do work. It is based on the idea that in any isolated system, anywhere in the universe, there is a measurable amount of internal energy. The internal energy is the sum of the KINETIC ENERGY and POTENTIAL ENERGY possessed by all the atoms and molecules within the system. This total amount of internal energy cannot change without intervention from outside the system, in which case the system ceases to be isolated. This principle can be described by four laws.

The first law of thermodynamics was suggested in the 1840s by the German physicist Julius Robert Mayer (1814–78, *see also* John Tyndall; APPENDIX I: BIOGRAPHICAL ENTRIES) and was verified in 1843 by the English physicist James Prescott Joule (1818–89). Lord Kelvin (1824–1907), the Scottish physicist, and the German physicist Hermann Ludwig Ferdinand von Helmholtz (1821–94) also made important contributions to the development of the law.

The first law states that energy can be neither created nor destroyed, but that it can be changed from one form into another. This is sometimes called the law of conservation of energy.

There was a difficulty with this law. Joule had measured the mechanical equivalent of heat, which is the change of energy from one form (heat) to another (kinetic energy). Heat engines, such as steam and internal combustion engines, exploit this transformation. The French theoretical physicist Nicolas-Léonard Sadi Carnot (1796–1832) had shown that the efficiency of such an engine depends only on the difference in temperature between the source of heat and the sink into which the heat is finally discharged. Some heat is lost, however, as energy flows through the engine. So where does the lost energy go, given that according to the first law energy cannot simply vanish? The loss was explained in 1850 by the German theoretical physicist Rudolf Clausius (1822–88). Clausius asserted that heat does not pass spontaneously from a colder to a hotter body. For example, if you leave a cup of hot coffee to stand in a cold room, the coffee will become colder by losing its heat, and not hotter by absorbing heat from its cold surroundings. In 1851, Lord Kelvin arrived at the same conclusion. The apparently lost energy is absorbed into the surrounding environment.

This is the second law of thermodynamics. There are several ways it can be expressed. Clausius summarized it in two ways: Heat cannot be transferred from one body to a second body at a higher temperature without producing some other effect; or to put it differently, the entropy of a closed system increases with time. Clausius coined the word *entropy.* The second law means that most physical processes are irreversible.

Entropy is a measure of the amount of disorder that is present in a system. As the amount of disorder increases, so does its entropy, and disorder increases all the time and has done so throughout the history of the universe. Entropy always increases because there is a much greater statistical probability that the random motion of atoms and molecules will lead them to form chance arrangements than that they will come together in highly organized structures. If a vase falls onto a stone floor, it will probably shatter into many pieces. This is a less ordered state than the one that existed when the fragments were joined seamlessly together and the vase was complete. The shattering of a vase is a common event and one that increases disorder. History records no instance of the fragments of a shattered vase spontaneously moving back together again to reconstruct the vase as it was before it fell.

Order can be described as a difference in energy level between an object and its surroundings. As entropy increases, this difference decreases. Consider what happens when a cup of hot coffee is left to stand on a table. The coffee cools until it is at the same temperature as the air around it. The energy difference between the coffee and the air has disappeared, and both are at the same energy level. It never happens that the hot coffee absorbs energy from the cooler air and its temperature increases.

In exactly the same way, when solar radiation warms the surface of the Earth that heat is dissipated. Some is lost immediately as infrared radiation (*see* BLACKBODY) into space and some warms the air in contact with the surface. This warming produces all our weather phenomena, but the energy driving the weather also dissipates, because the atmospheric gases also radiate energy into space. The weather continues because there is a constant supply of solar energy to drive it. Without that energy, the Earth would cool until it was at the same temperature as the space surrounding it.

Entropy means that most everyday events are irreversible. For this reason it is sometimes known as the "arrow of time."

Entropy increases, and so there must be a point at which it reaches a maximum and can increase no further. This point is described by the third law of thermodynamics, which was discovered in 1905–06 by the German physical chemist Hermann Walther Nernst (1864–1941).

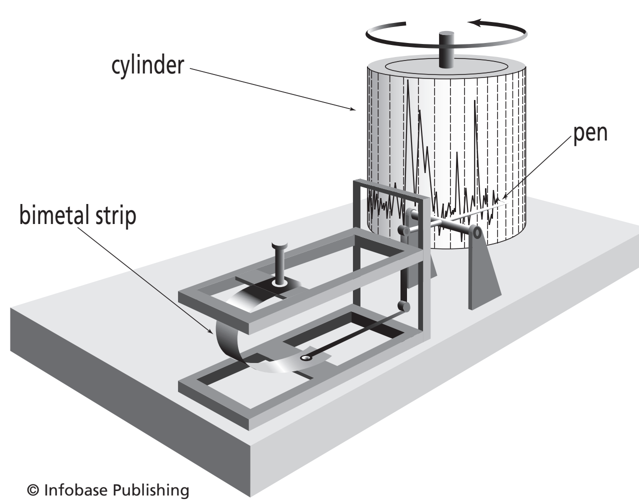
The third law states that in a perfectly crystalline solid there is no further increase in entropy when the temperature falls to absolute zero (*see* TEMPERATURE SCALES). This also means that it is impossible to cool any substance to absolute zero (although substances have been cooled to a tiny fraction of a degree above absolute zero).

The discovery of the third law should have completed the list of laws of thermodynamics, but there is a further principle that is more fundamental than any of them. It had been well known for centuries and was taken for granted until the English physicist Sir Ralph Fowler (1889–1944) drew attention to it. It could not be called the fourth law, because it is the principle that underlies the second law (and it can be derived from it). Nor could it be called the first law, because that would mean renumbering the existing laws, which would cause endless confusion. So Fowler proposed that it be called the zeroth law (law number 0).

The zeroth law states that if two isolated systems are each in thermal equilibrium with a third, then they are in thermal equilibrium with each other. Thermal equilibrium is the condition of two or more bodies that are at the same temperature and therefore possess the same amount of kinetic energy. Unless some outside process intervenes, energy will not be exchanged between bodies that are in thermal equilibrium.

This law makes it possible to use a THERMOMETER to measure the temperature of a substance or body. The thermometer is an isolated system that is brought into equilibrium with the system being measured, and the temperature scale marked on the thermometer is derived from a third system that was used to calibrate the instrument.

thermograph A thermograph is an instrument which provides a continuous record of TEMPERATURE. It consists of a component that changes shape with changes in temperature. This component is connected by a system of levers to an arm that terminates in a pen held against a calibrated chart mounted around a cylinder. The cylinder rotates at a constant speed, so the pen



A thermograph provides a continuous record of temperature as a line drawn by a pen on a chart attached to a cylindrical drum.

traces around the chart a line that rises and falls with temperature changes.

The principal component may be a bimetal strip or a Bourdon tube. A bimetal strip consists of two pieces of different metals that expand and contract by widely different amounts when heated and cooled. The two strips are bonded together, so that their differential expansion and contraction causes the combined strip to bend. A Bourdon tube is a curved container made from phosphor bronze and filled with alcohol. Like a bimetal strip, it bends in response to changes in temperature.

thermohaline circulation The thermohaline circulation is the exchange of surface and deep water that takes place in the oceans, but only in high latitudes, due to differences in temperature (*thermo-*) and salinity (*-haline*).

Over most of the oceans, the surface layer remains warmer than the deep water at all times, because it absorbs solar radiation. This means that the surface layer, being warmer and therefore less dense, mixes only slightly with the water below it. The warmer the surface layer, the greater is the difference in DENSITY between the surface and deep water. Consequently, very little mixing can occur between the surface and deep waters in the tropical oceans, but rather more in mid-latitude oceans.

In Arctic and Antarctic waters, however, the surface layer loses so much heat by radiating it toward the sky that it becomes colder than the water beneath it. As it freezes, salt is expelled from the ice crystals and into the water adjacent to the ice. Water near the ice is therefore colder than the subsurface water and also more saline. Both factors increase its density, so this water sinks and deep water rises to take its place, establishing a thermohaline circulation. This vertical circulation is also known as convective overturning.

In the North Atlantic, the cold, saline water sinks all the way to the ocean floor, where it forms the NORTH ATLANTIC DEEP WATER (NADW). The NADW flows southward as a slow-moving current all the way to the Southern Ocean, thus forming the movement of water that drives the GREAT CONVEYOR.

The thermohaline circulation in the North Pacific Ocean is very weak, and there is no convective overturning, because there the surface waters are too fresh to sink. Dense, saline water sinks near the edge of the ice in the Southern Ocean, but there the effect is greater than in the North Atlantic due to a high rate of evaporation and also the possibility that water becomes supercooled (*see* SUPERCOOLING) and sinks at the base of the ice shelves.

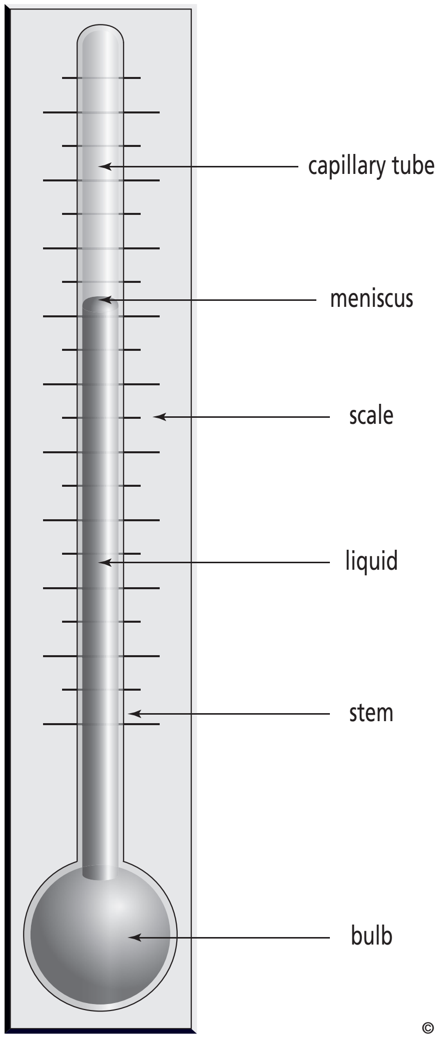
thermometer A thermometer is an instrument that is used to measure the TEMPERATURE of a substance. Thermometers used in METEOROLOGY are used to measure the temperature of AIR and WATER. The measurement of air temperature by instruments that are mounted on aircraft is called aircraft thermometry.

There are several ways to measure changes in temperature. The most common method is based on the fact that many substances expand when they are warmed and contract when they are cooled. If this property is to be used to measure small changes in temperature, the substance chosen must expand and contract by the largest amount possible. Air was the first to be tried, in the air thermoscope that was invented by Galileo (*see* APPENDIX I: BIOGRAPHICAL ENTRIES).

Galileo's air thermoscope consisted of a glass bulb connected to a narrow glass tube that was mounted vertically with its lower end immersed in colored water contained in a sealed vessel. Air in the bulb expanded and contracted as the temperature rose and fell, pushing the water in the tube downward as it expanded and drawing it upward as it contracted. The thermoscope was very sensitive to changes in temperature, but it made no allowance for changes in AIR PRESSURE that also alter the volume of air, and so it was very inaccurate. Consequently, the air thermoscope was very inaccurate.

Liquids were found to be better than air. In 1641, Ferdinand II of Tuscany (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), a contemporary of Galileo, used liquid to make the first reliable thermometer. Ferdinand used alcohol, and in 1714 Daniel Fahrenheit (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) made a similar thermometer using mercury. His was the first thermometer to give readings that were both reliable and accurate, and Fahrenheit is credited with having invented the thermometer.

Until recently, both alcohol and mercury were used, but mercury is no longer permitted because it poses a risk to health. Alcohol expands and contracts more than mercury does, but an alcohol thermometer is less accurate than a mercury thermometer. This is because the rate at which substances expand with increasing temperature varies slightly across the temperature



The most widely used thermometer measures the expansion of a liquid held in a reservoir, called the bulb, opening into a capillary tube. The expansion and contraction of the liquid are read against a scale.

range, and the variation, although small, is greater for alcohol than for mercury. Both alcohol and mercury remain liquid at temperatures encountered in the lower atmosphere. A dye is added to alcohol to make it visible. Most alcohol thermometers use a red dye, but some use blue.

Alcohol and mercury thermometers consist of a narrow capillary tube (*see* CAPILLARITY), sealed at one end and blown into a bulb at the other end. The bulb acts as a reservoir for the liquid. As the liquid expands and contracts, the change is exaggerated by the narrowness of the tube in which it moves.

The thermoscope failed because Galileo did not know that the volume of a body of air changes with the atmospheric pressure as well as with the temperature. Account can now be taken of this factor, and modern gas thermometers are the most accurate of all thermometers that are based on the changing volume of a fluid. The gas used is not air, but either NITROGEN, HYDROGEN, or HELIUM. It is held in a vessel, so its volume remains constant. As the temperature changes, the pressure the gas exerts also changes according to the GAS LAWS, and this is the change that is registered. Gas thermometers are used in industry.

The amount by which the volume of a substance changes with changing temperature is called the coefficient of thermal expansion of that substance. This varies greatly from one substance to another. As the temperature changes, two metals with different coefficients of thermal expansion will increase and decrease in length by different amounts. If strips of these metals are securely bound together into a bimetal strip, as the length of one strip changes more than that of the other, the bimetal strip will curl by an amount proportional to the change in temperature. This property provides the basis for a thermometer using a bimetal strip. It is often used to operate thermostats. Its principal meteorological use is in THERMOGRAPHS. A bimetal strip is less accurate than an alcohol or mercury thermometer, however.

The properties of dissimilar metals can also be used to measure temperature electrically. A thermocouple consists of two wires or rods of different materials, each of which is made into a half loop. The two half loops are welded together at their ends to make a circuit. If one of the joints is at a different temperature from the other, an electric current flows through the circuit. This phenomenon was discovered in 1821 by the Estonian–German physicist Thomas Johann Seebeck (1770–1831) and is known as the Seebeck effect. The first thermometer to use it was made in 1887 by the French physical chemist Henri-Louis Le Châtelier (1850–1936), using platinum and rhodium as the two metals.

As the temperature of a metal rises, the electrical resistance of the metal increases. This property is exploited to make resistance thermometers, commonly using platinum, nickel, tungsten, copper, or alloy wires. Resistance thermometers are accurate to within 0.2°F (0.1°C).

Ceramic semiconductors have a similar property. They are used to make thermistors. The principal component in a thermistor is an electronic device that resists the flow of an electric current by an amount that varies with the temperature. As the temperature rises, the resistance increases, and the current flowing through the device decreases. As the temperature falls, the resistance decreases, and the current increases.

The Beckman thermometer is used for measuring very small changes in temperature. It is a mercury-in-glass thermometer with two bulbs. One bulb is located at the bottom of the thermometer tube, as in an ordinary thermometer. The top of the tube is shaped like an inverted U and the other, smaller bulb is at the end of one arm of the U. At the base of the upper bulb there is a second, upright, U-shaped tube. Mercury can be run from the upper bulb into the lower one. This alters the range of temperature the thermometer measures. The scale covers only about 9°F (5°C). The thermometer was invented by the German chemist Ernst Otto Beckman (1853–1923).

Once a thermometer has been made it must be calibrated. This is usually done by marking the position of the liquid at two reference temperatures, called fiducial points, commonly the freezing and boiling temperatures of pure water under standard sea-level atmospheric pressure. The distance between these two points is then divided into a convenient number of gradations, called degrees. Three calibration systems are in common use. The Fahrenheit TEMPERATURE SCALE is still popular in the United States and Britain, but it is being replaced by the Celsius temperature scale, which is the one used in the rest of the world. Scientists use the Kelvin scale.

It is sometimes useful to record not only the present temperature, but also the highest and lowest temperatures that have occurred during a given period, for example of 24 hours. A maximum–minimum thermometer makes this possible. It consists of two thermometers mounted side by side.

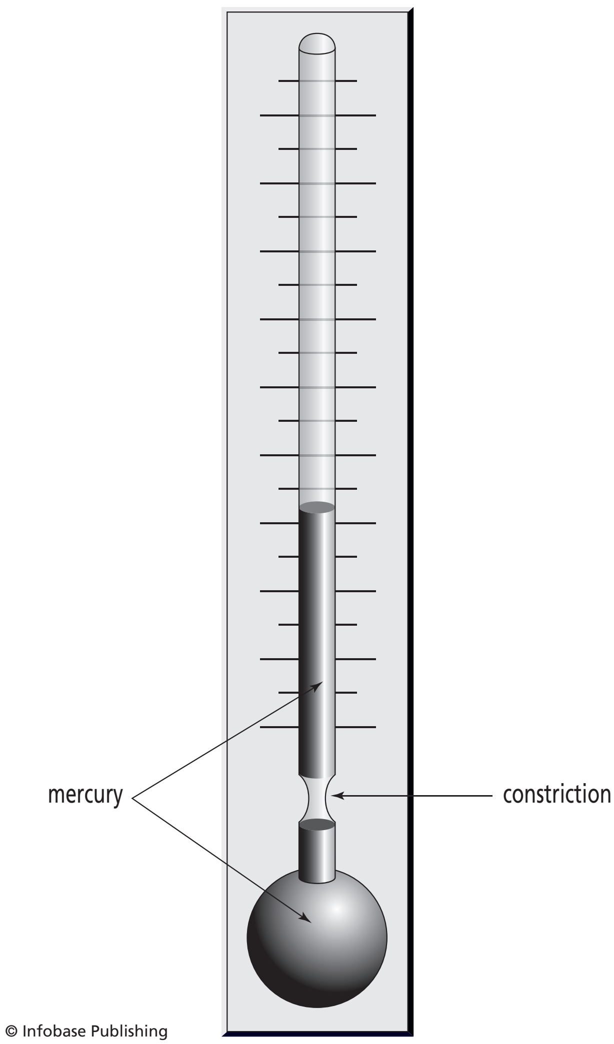
The maximum thermometer records the highest temperature reached during the time since it was last reset. The thermometer uses mercury in a tube that has a constriction. As the temperature rises, the force with which mercury expands is sufficient to push it past the constriction. As the temperature falls, however, the mercury is unable to pass the constriction and return to the bulb, so it continues to indicate the highest temperature attained. Shaking the thermometer to jerk the mercury through the constriction and back into the bulb resets it.

A minimum thermometer records the lowest temperature reached since it was last reset. The thermometer contains a fluid with a low density, most commonly colored alcohol. Inside the thermometer tube there is a small strip of metal, often in the shape of a dumbbell, called the "index." When the temperature falls, the liquid contracts toward the bulb. As the upper surface of the liquid reaches the top of the index, the index is drawn down the tube by SURFACE TENSION. When the temperature rises, the liquid flows past the index, leaving it in the position it reached when it was drawn toward the bulb. The tip of the index farthest from the thermometer bulb therefore registers the lowest temperature attained. To reset the thermometer, it is held vertically with the bulb uppermost. The index then sinks to the top of the liquid.

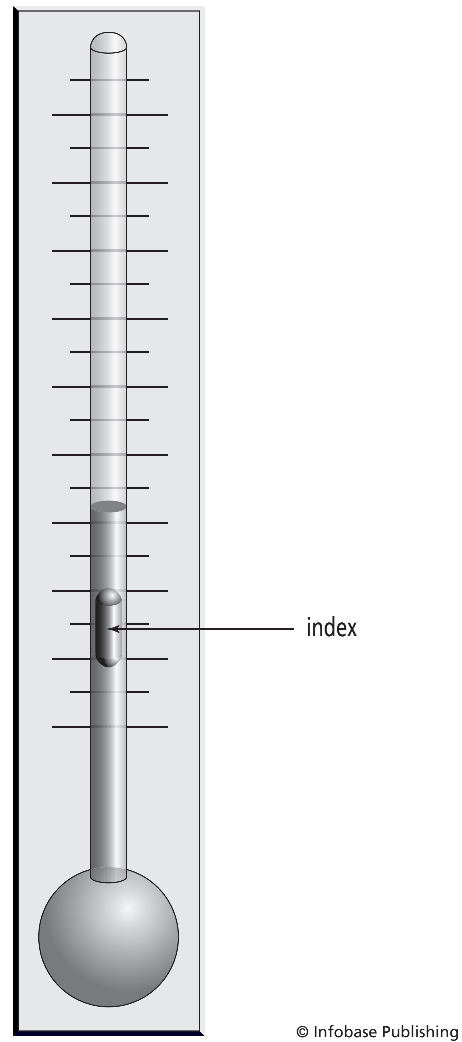
Alternatively, some minimum thermometers use an iron index that is repositioned by using a small magnet to drag it. Because the index can move along the tube by gravity, the most accurate minimum thermometers must be mounted horizontally.

Thermometers can also measure the rate at which water evaporates and the relative HUMIDITY and DEW point temperature can be calculated from the resulting reading. This also requires two thermometers, one with a dry bulb and the other with a wet bulb. The resulting instrument is known as a psychrometer (*see* PSYCHROMETRY).

A wet-bulb thermometer is fitted with a layer of wetted cloth around its bulb. The cloth is usually muslin, and it extends below the bulb, where it is immersed in a reservoir of distilled water, so it acts as a wick. Water is drawn into the wick by capillarity and evaporates from it, thus maintaining a constant amount of moisture around the bulb provided the reservoir does not run dry, and there is a free circulation of air around the cloth. The LATENT HEAT of vaporization is taken from the thermometer bulb. This depresses the temperature registered by the thermometer. The difference between the temperature that is registered by a dry-bulb thermometer and that registered by a wet-bulb thermometer adjacent to it is known as the wet-bulb depression. The extent of the wet-bulb depression indi-



In a maximum thermometer, the liquid is able to expand past the constriction, but not to contract past it. Consequently, the thermometer registers the highest temperature reached since it was last reset.



In a minimum thermometer, as the temperature falls and the liquid contracts the index is drawn toward the bulb. As the temperature rises, the liquid flows past the index, leaving it in position.

cates the rate of EVAPORATION, which varies according to the atmospheric humidity.

thickness In METEOROLOGY, thickness refers to the difference in altitude between two CONSTANT-PRESSURE SURFACES. This difference varies with the temperature of the air, because the warmer air is the less dense it is, which means that a given mass of warm air occupies a greater volume than a similar mass of cold air. Consequently, a layer of warm air bounded by two constant-pressure surfaces will be thicker than a layer of cold air bounded by the same surfaces. The resulting gradient is responsible for generating the THERMAL WIND.

A line drawn on a map that joins places where the thickness of a given atmospheric layer is the same is called a thickness line, also known as a relative isohypse. The pattern that is made by the thickness lines on a thickness chart (*see* WEATHER MAP) is called the thickness pattern, or relative hypsography.

Thomson effect A water molecule at the surface is more tightly bound in a body of liquid that has a plane (level) surface than it is in a spherical droplet, and the smaller the droplet the easier it is for the molecule to escape. The effect was first described mathematically by the Scottish physicist William Thomson (1824–1907), who later became Lord Kelvin. (It should not be confused with the Thomson effect in thermodynamics, which was also discovered by Lord Kelvin.)

The equation describing the Thomson effect is:

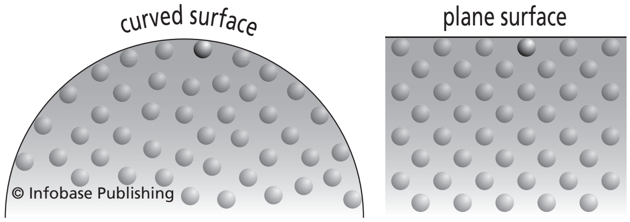
$$\rho_r/\rho s = \exp\,(A/rT)$$

where ρ_r is the equilibrium vapor density (*see* BOUNDARY LAYER), ρ_s is the density at SATURATION of the layer adjacent to it, A is a constant for the liquid, r is the radius of curvature of the droplet, T is the absolute temperature (*see* TEMPERATURE SCALES), and exp indicates that the relationship is EXPONENTIAL.

The forces that bind water molecules are exerted in all directions. Molecules at a plane surface are attracted from the sides and from below, but there are no molecules to attract them from above. A molecule at a curved surface is also attracted from below and from the sides, but because of the curvature molecules to the sides are also a little below it, and so the lateral attraction is reduced. This means it is easier for a molecule to escape into the air from a curved surface than from a plane surface. The smaller the radius of curvature, the greater the reduction in the lateral attraction.

The ratio of ρ_r to ρ_s increases as the radius of curvature (r) decreases and the droplet becomes smaller. Consequently, the smaller the droplet, the more water molecules that will escape from the equilibrium vapor around it into the air beyond and droplets can survive only if ρ_s increases until it is greater than ρ_r. In other words, the air surrounding the droplet must be supersaturated.

Water molecules have a definite size, which limits the minimum size it is possible for a droplet to be. When this is taken into account, it is found that spontaneous nucleation of liquid droplets (*see* CONDENSATION) can occur only when the relative HUMIDITY (RH) reaches about 300 percent. Air is never this humid. The fact that water vapor is able to condense so readily demonstrates the importance of CLOUD CONDENSATION NUCLEI to the process of condensation.



A molecule at the surface of a spherical droplet is bound to the liquid less strongly than a molecule at a plane surface.

The exponential nature of the relationship between ρ_r and ρ_s is critical. As soon as r begins to increase, by only the smallest amount, condensation accelerates rapidly. Once a droplet has a radius of 0.15 µm (0.000006 inch) an RH of 101 percent is sufficient for it to grow.

The Thomson effect can be modified by RAOULT'S LAW when the droplet is not of pure water, but is a solution. Where a mass (m) of a solute is dissolved in a droplet of water, the overall effect is modified by a constant (B) that is determined by the composition of the solute. The equation is then:

$$\rho_r/\rho_s = 1 + (A/rT) - (Bm/r^3)$$

Thornthwaite climate classification The Thornthwaite climate classification is a scheme for classifying climates that was devised by C. W. Thornthwaite (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). The first version of the scheme, published in 1931, applied only to North America, but in subsequent years it was expanded to cover the entire world.

Like the KÖPPEN CLIMATE CLASSIFICATION, the Thornthwaite classification is generic, in that it uses quantitative criteria of TEMPERATURE and PRECIPITATION to define the boundaries of climatic types. It differs from the Köppen classification in its use of the concepts of precipitation efficiency and thermal efficiency, but its most important contribution came in the 1948 revision of the scheme, in which Thornthwaite introduced the concept of potential EVAPOTRANSPIRATION and a moisture index.

In the Thornthwaite scheme, precipitation efficiency (PE) is calculated as the sum of the ratios of precipitation (P) to evaporation (E)—the amount of water that evaporates from an exposed water surface in the course of one month—for each month through the year. Evaporation varies according to the temperature, so temperature is included in the calculation. Precipitation efficiency is equal to $115(r/t - 10)^{10/9}$, where r is the mean monthly rainfall in inches and t is the mean monthly temperature in °F. This calculation is made for each month and the sum of the indexes for 12 months gives the precipitation-efficiency index (P-E index), which is a value indicating the amount of water that is available for plant growth through the year.

The moisture index (Im) is a value that is calculated to show the monthly surplus or deficit of water in the soil. It is given by: $Im = 100(S - D)/PE$, where S is the monthly water surplus (*see* SOIL MOISTURE), D the monthly water deficit, and PE is the potential evapotranspiration. It can also be calculated from: $Im = 100(r/PE - 1)$, where r is the annual precipitation.

Thornthwaite also introduced the humidity index, which is a measure of the extent to which the amount of water available to plants exceeds the amount needed for healthy growth. It is calculated as $100W_s/PE$, where W_s is the water surplus and PE is the potential evapotranspiration.

A humidity province is one of the five categories into which climates are divided on the basis of their precipitation efficiency index value. The five provinces are labeled A, B, C, D, and E. Province A, with a P-E index greater than 127 is the rain forest climate. B, with a P-E index of 64-127, is the forest climate. C, with a P-E index of 32–63, is the grasslands climate. D, with a P-E index of 16–31, is the steppe climate. E, with a P-E index of less than 16, is the desert climate.

Thermal efficiency similarly relates temperature (T) to evaporation to yield a thermal-efficiency index (T-E index). Because temperature and evaporation are so closely linked, the T-E value is shown in the table of climate types as the potential evapotranspiration. The thermal-efficiency index indicates the amount of energy, as heat, that is available for plant growth in the course of a year. It is calculated from measurements of the amount by which the mean temperature in each month is above or below freezing. For each month the thermal efficiency is $(t - 32)/4$, and the thermal-efficiency index is the sum of the thermal efficiencies for each month through the year. A value of 0 indicates what is called a frost climate, and a value of more than 127 indicates a tropical climate.

From these calculations, Thornthwaite recognized nine moisture provinces based on the P-E index, and 9 temperature provinces based on the T-E index. These are given names and also designated by letters and numerals. The moisture provinces are related to vegetation and correspond to rain forest (A), four types of forest (B), two types of grassland (C), steppe (D), and desert (E).

In addition, the classification adds code letters that qualify these main categories by referring to the amount and distribution of precipitation associated with them. This brings to 32 the total number of climate types recognized in the scheme. These additional qualifications are based on an aridity index for moist climates and a humidity index for dry climates.

Moisture Provinces

Climate type		Moisture index
A	perhumid	100 or more
B_4	humid	80–100
B_3	humid	60–80
B_2	humid	40–60
B_1	humid	20–40
C_2	moist subhumid	0–20
C_1	dry subhumid	-20–0
D	semi-arid	-40–20
E	arid	-60–40

Temperature Provinces

Climate type		Potential evapotranspiration inches	Potential evapotranspiration centimeters
E′	frost	5.61	14.2
D′	tundra	11.22	28.5
C'_1	microthermal	16.83	42.7
C'_2	microthermal	22.44	57.0
B'_1	mesothermal	28.05	71.2
B'_2	mesothermal	33.66	85.5
B'_3	mesothermal	39.27	99.7
B'_4	mesothermal	44.88	114.0
A′	megathermal	>44.9	>114

Moist climates (A, B, C_2)		Aridity index
r	little or no water deficiency	0–16.7
s	moderate water deficiency in summer	16.7–33.3
w	moderate water deficiency in winter	16.7–33.3
s_2	large water deficiency in summer	more than 33.3
w_2	large water deficiency in winter	more than 33.3

Dry climates (C_1, D, E)		Humidity index
d	little or no water surplus	0–10
s	moderate water surplus in winter	10–20
w	moderate water surplus in summer	10–20
s_2	large water surplus in winter	more than 20
w_2	large water surplus in summer	more than 20

The moisture provinces, temperature provinces, and moist and dry types of climate are shown in the tables above.

THORPEX The Observing System Research and Predictability Experiment (THORPEX) is the successor to the GLOBAL ATMOSPHERIC RESEARCH PROGRAMME (GARP). It was established in May 2003 by the 14th World Meteorological Congress under the auspices of the WORLD METEOROLOGICAL ORGANIZATION (WMO) Commission for Atmospheric Sciences. It is a component of the WMO World Weather Research Programme (WWRP).

THORPEX is planned to run for 10 years, until 2013. During this time it will conduct experiments aimed at improving short-range (up to 3 days) and medium-range (3–10 days) deterministic and probabilistic forecasts of extreme weather in the Northern Hemisphere. The THORPEX projects will study the ways in which satellite and surface observations acquire data and how those data are assimilated. The overall objective is to ensure that weather forecasts are timely and accurate, and that they are translated into specific information that supports practical decisions to reduce the loss of life, injuries, and property losses associated with extreme weather events such as TROPICAL CYCLONES, BLIZZARDS, FLOODS, and DROUGHTS.

Further Reading

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thunder Thunder is the sound caused by the discharge of energy during a LIGHTNING flash. As the flash moves along its lightning channel, it raises the temperature of the ionized (*see* ION) air inside the channel by up to 54,000°F (30,000°C) in less than one second. This causes the air to expand violently, increasing the pressure inside the channel to as much as 100 times its normal value. The expansion is so rapid as to be explosive, and it emits shock waves that immediately become the sound waves people hear as thunder.

Sound waves travel at about 670 MPH (1,080 km/h), which is the speed of sound in air. Light from the flash travels at the speed of light, which is approximately 1 million times faster. Consequently, a distant observer sees the lightning flash before hearing the clap of thunder associated with it. By counting the time that elapses between seeing the lightning and hearing the thunder, it is possible to calculate the approximate distance to the storm: every five seconds represents a distance of about one mile (three seconds per kilometer).

As they travel, the sound waves are damped by the air. Those with a short wavelength (*see* WAVE CHARACTERISTICS), carrying sounds of a high pitch, disappear before those with a long wavelength, carrying the low pitches. The greater the distance from the lightning, therefore, the deeper the note of the thunder. Very distant thunder is heard as a deep rumble.

The sound often continues for several seconds. That is because of the length of the lightning flash that causes it. A lightning flash can be more than a mile (1.6 km) long, and its forked shape means some parts of it are closer to the observer than others. Sound from the nearest part of the flash reaches the observer first, and sound from the more distant parts arrives later, extending the duration of the sound.

Thunder can seldom be heard from more than about 6 miles (10 km) away, because by then all the sound waves have been either absorbed by the air or refracted upward by the effect of the decrease in air temperature with height. Lightning can be seen over a much greater distance, especially at night. Silent flashes of sheet lightning are most often seen on warm summer nights and are sometimes called "heat lightning."

The cause of thunder puzzled people for centuries. Germanic peoples believed it was the sound of the god Thor, either beating his huge anvil or throwing his hammer at other gods. The word *thunder* is from the Old Norse *thórr.* According to a poem called *De Rerum Natura* ("On the Nature of Things") written in about 55 B.C.E. by the Latin poet Lucretius (his dates of birth and death are not known, but his full name was Titus Lucretius Carus) thunder is the sound of great clouds crashing together. Native Americans thought it was the sound of huge thunderbirds flapping their wings.

thunderbolt A thunderbolt is a rock, piece of metal, or dart that storm gods such as Zeus (Jupiter), Yahweh (Jehovah), and Thor were once believed to hurl at the Earth. As they traveled through the air, thunderbolts could be seen as LIGHTNING, and they were believed to cause the damage that occurs when lightning strikes an object or person.

When lightning strikes sand, the sudden discharge of energy is often sufficient to melt the grains, producing an irregular mass of glass coated in sand grains called a fulgurite. Fulgurites are usually about half an inch (1 cm) in diameter, with side branches. Most are less then 10 feet (3 m) long, but they can be more than 60 feet (18 m) long. A piece of such glass was assumed to be a thunderbolt.

In ancient Greece and Rome the area around a lightning strike was fenced off and considered sacred, and persons killed by lightning were buried where they died, rather than in the usual burial ground. It was not until 1752 that the true, electrical nature of lightning was proved by Benjamin Franklin (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) and, independently, by the French scientist Thomas-François d'Alibard (1703–99) and the link between storm gods and so-called thunderbolts was shown to be entirely mythical.

thunderstorm A thunderstorm is a violent storm that causes THUNDER and LIGHTNING as well as heavy PRECIPITATION and strong GUSTS of wind. Every day more than 16 million thunderstorms occur in the world as a whole, and about 2,000 are taking place at any moment. About 100,000 thunderstorms occur in the United States every year. A day on which a thunderstorm is observed at a WEATHER STATION is known as a thunderstorm day.

Development of a thunderstorm begins with the growth of cumulus clouds (*see* CLOUD TYPES). Inside such clouds warm air is rising by CONVECTION. As it rises, the air cools adiabatically (*see* ADIABAT) and some of its WATER VAPOR condenses. This releases LATENT HEAT of CONDENSATION, warming the surrounding air and causing it to continue rising.

The cloud builds rapidly, with updrafts traveling at up to 100 MPH (160 km/h). The very strong upcurrent found in a rapidly developing cumulus cloud is called an uprush or a vertical jet. A cloud with an uprush is likely to grow into a cumulonimbus and produce a thunderstorm.

As the upper part of the cloud grows past the FREEZING LEVEL, the Bergeron–Findeisen mechanism (*see* RAINDROPS) causes precipitation to commence. The precipitation may fall as HAIL, the size of the hailstones indicating the vertical extent of the cloud and the force of its upcurrents. There will also be RAIN or SNOW depending on the temperature in the lower part of the cloud and in the air between the cloud base and the surface. The precipitation, in whatever form, is carried in the downdraft through the base of the cloud.

An isolated severe thunderstorm in central Oklahoma. The core of the storm, containing the main updraft, is in the background. The cloud in the foreground is the incus, or storm anvil. ***(NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory [NSSL])***

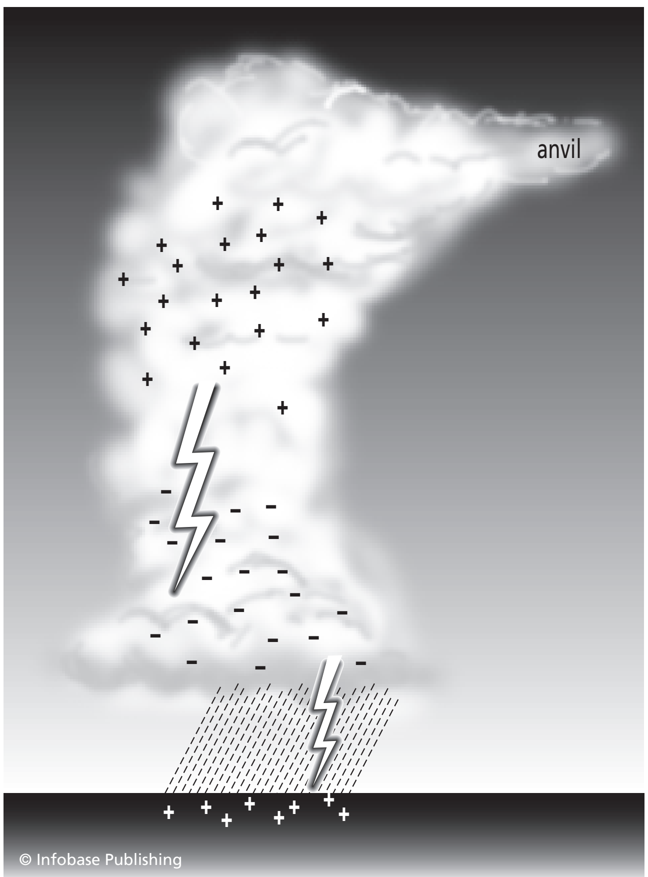
By this stage the cloud has become a cumulonimbus, and it extends vertically to a height of 50,000 feet (15 km) or more. Upper-level winds draw out the ICE CRYSTALS at its top into an anvil (incus) shape. The storm is then in its most active stage.

A small area of low AIR PRESSURE found to the rear of a fully developed thunderstorm is called a wake low. It develops because the cold downdrafts at the leading edge of the advancing thunderstorm produce a local area of high pressure, and air is drawn into the rear of the storm to compensate, producing low surface pressure where the air begins to rise. Wake lows form behind the main cloud mass and are associated with clearing skies and the end of the precipitation. They are common behind SQUALL line storms.

The storm derives its energy from the latent heat of condensation, so it requires a constant inflow of warm, moist air to sustain it. Once precipitation commences, the falling raindrops, ice crystals, and hailstones drag with them small envelopes of chilled air. These accumulate and form downdrafts, carrying cold precipitation and cold air out of the base of the cloud. Some of the precipitation evaporates as it falls, drawing the latent heat of vaporization from the surrounding air and cooling it further. The location in a thunderstorm where air that has been cooled by the EVAPORATION of moisture meets warm, moist air is called the outflow boundary.

As the precipitation intensifies, so do the downdrafts. These fall into the updrafts and eventually come to dominate the cloud and suppress the updrafts by cooling the rising air. The storm is then deprived of energy and the cloud is deprived of moist air. The precipitation becomes lighter and the cloud begins to dissipate.

It is while it is in its most active stage that the storm produces lightning. This occurs because electrical charge becomes separated inside the cloud. Positive charge accumulates in the upper regions and negative charge in the lower regions. The negative charge near the base of the cloud induces a positive charge on the ground beneath the cloud. Lightning consists of electrical discharges between the separated charges. This neutralizes them, but only temporarily in an active storm.



Electric charge has become separated inside the cumulonimbus cloud. Positive charge accumulates in the upper part of the cloud, negative charge in the lower part, and the negative charge induces a positive charge on the ground surface beneath the cloud. Lightning is the spark that partly neutralizes the charge distribution. Near the tropopause, the top of the cloud is swept into an anvil shape by the wind.

It takes no more than about 20 seconds for the charges to separate again.

Scientists are not certain what it is that causes charge separation, but it is known that the small particles or droplets acquire positive charge and the large ones acquire negative charge. It is gravity that separates them, therefore, as the heavy ones sink to the bottom and the light ones are carried to the top. When a droplet freezes, positive ions migrate toward the colder regions, leaving the less mobile negative ions in the warmer regions. Liquid droplets freeze from the outside in, so a shell of positive charge surrounds a core of negative charge. As the core starts to freeze, it expands, shattering the shell into minute fragments. The fragments carry their positive charge upward, and the heavier core carries its negative charge downward.

It may also happen that small ice splinters collide with hailstones the outsides of which have been warmed by the release of latent heat as supercooled water (*see* SUPERCOOLING) freezes onto them. At each collision positive ions move toward the colder end of the splinter. This increases the negative charge both at the warmer end of the splinter and on the hailstone. The charge changes by only a very small amount at each collision, but the very large number of collisions means there is a big cumulative effect. The splinters, with their positive charge, are carried upward and the hailstones, with their negative charge, drift downward.

There may also be an upward flow of ions carrying positive charge from tall objects such as trees and buildings. This is called a point discharge, and it is induced by the negative charge at the base of a cloud that is producing a thunderstorm. Point discharge is the more important of the two processes that produce a negative charge at the surface of the Earth (the other is lightning) and in this way replenish the charge lost as positive ions are conducted downward through the air from the ionosphere (*see* ATMOSPHERIC STRUCTURE). In the absence of point discharges and, to a lesser extent, lightning strokes, within about 15 minutes the surface would acquire a positive charge equal to that in the ionosphere and the Earth's electrical field would break down. Occasionally a point discharge is strong enough to be visible as a glow, known as Saint Elmo's fire, around the structure from which it flows. This is sometimes seen near the top of a ship's mast.

An AIR MASS thunderstorm results from convection in unstable air (*see* STABILITY OF AIR). The cumulonimbus cloud producing the storm grows vertically, and probably lacks an anvil because there is no change in wind speed with height. The storm is produced entirely by conditions pertaining to the air mass. This type of storm is frequent in the TROPICS. It is also the type of storm that occurs in middle latitudes late on summer afternoons when the air is humid and the ground has been strongly heated, making the air above it unstable. This type of thunderstorm is sometimes called a heat thunderstorm.

An advective thunderstorm is one triggered by the ADVECTION of warm air across a cold surface, or of cold air above a layer of warmer air at a high level. Warm air is cooled when it crosses a cold surface. This causes its water vapor to condense, releasing latent heat, which may make the air sufficiently unstable to produce cumulonimbus cloud. Cold air moving above warm air may also cause instability as it sinks beneath the warmer air, thus raising it and causing the warm air to cool adiabatically (*see* ADIABAT) and its water vapor to condense.

A frontal thunderstorm is one that develops in warm, moist air that has been made unstable by frontal lifting. Such storms can be violent and where the cold FRONT is advancing very fast and pushing vigorously beneath the warm front, the rapid lifting along a substantial frontal length can produce a squall line. A surge line is a line just ahead of a local group of thunderstorms where there is a sudden change in the wind speed and direction. A cold front thunderstorm is produced on a cold front. As cold air pushes beneath warm air, or warm air rises over cold air, moist air in the warm sector may become sufficiently unstable to generate cumulonimbus clouds that are vigorous enough to cause storms.

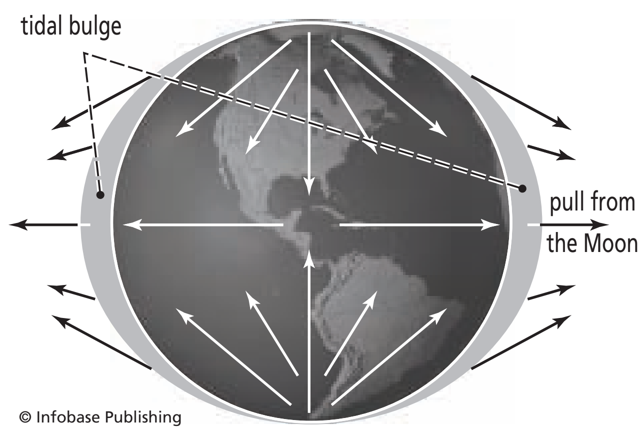
Tibetan high An ANTICYCLONE, called the Tibetan high, develops in summer over the Tibetan Plateau. In early summer the ground warms strongly. Air rises by CONVECTION, producing a shallow layer of low pressure near the ground and high pressure at heights above the 500-millibar level. The anticyclonic flow (*see* ANTICYCLONE) is from the east on the southern side of the anticyclone. This contributes to the breakdown of the westerly JET STREAM. The change from a midlatitude westerly flow to an easterly flow and the disappearance of the jet stream are linked to the onset of the MONSOON over southern Asia and the mai-u rains over China (*see* LOCAL CLIMATES).

tides Tides are the regular movements of surface waters, the atmosphere, and the solid Earth that are caused by the gravitational attraction of the Moon and, to a lesser extent, of the Sun. This attraction produces two bulges at the surface. The bulges move around the Earth in step with the ORBIT of the Moon, producing two tidal cycles in every 24-hour period.

Tidal forces affect the liquid core of the Earth, and the resulting Earth tides can be measured by the bulges they produce in surface rocks. These are small, however, the greatest tidal movement nowhere exceeding about 3 feet (1 m). ATMOSPHERIC TIDES are synchronized to the daily solar cycle, rather than the lunar cycle. It is in the oceans that the tides are most clearly seen.

All the parts of the Earth, including the atmosphere and oceans, are drawn toward the center of the Earth by the gravitational force. Because the Earth is rotating, the gravitational force balances the inertial tendency of a moving body to continue to move in a straight line (*see* CENTRIPETAL ACCELERATION).

Both the Moon and Sun also exert a gravitational force. Their effect is much smaller than that of the Earth's own gravitational force, because gravity is subject to the INVERSE SQUARE LAW, which means that magnitude decreases rapidly with increasing distance. Lunar and solar gravity act in the opposite direction to terrestrial gravity and therefore reduce its magnitude. This effect alters the balance between the terrestrial



Lunar gravity reduces the magnitude of terrestrial gravity. Because the earth is rotating, this increases the tendency of every part of the Earth to continue moving in a straight line and fly away into space. The result is two bulges, produced where terrestrial and lunar gravity pull in opposite directions. One bulge is directly beneath the Moon, and the other is on the opposite side of the Earth.

gravitational force and the inertial tendency of each part of the Earth, producing two bulges in the oceans. One bulge lies on the surface of the Earth that is directly beneath the Moon. The lunar attraction acts in a straight line, reducing the magnitude of terrestrial gravity everywhere along that line. Consequently, the other bulge lies on the side of the Earth directly opposite the Moon. As the Moon orbits the Earth, the two bulges follow it.

The Moon takes 24 hours and 50 minutes to orbit the Earth, so high and low tides occur at intervals of 12 hours 25 minutes, which is why the times of the tides change from day to day. The declination (*see* PLANE OF THE ECLIPTIC) of the Moon changes during the month and is sometimes as much as 28.5°. This means that the lunar gravitational attraction acts at an angle to the equator, and therefore the tidal bulge is also at an angle to the equator. At any location on the surface of the Earth, therefore, one tide will rise higher than the other tide, and the two tides will have the same amplitude only when the Moon is directly above the equator.

The time of slack water, when the tide is about to turn, is called the stand of the tide. During this short period the height of the tide does not change, and tidal currents slow down and then cease before starting to flow again in the opposite direction.

The gravitational force exerted by the Sun is about 47 percent of the force exerted by the Moon. This is because, despite being much more massive than the Moon, the Sun is also much more distant. That is why the lunar influence on tides predominates.

The influence of the Sun is felt at times of spring and neap tides. Spring tides occur when the Earth, Sun, and Moon are aligned, so the gravitational influence of the Sun is added to that of the Moon. The approximate alignment of the Earth, Sun, and Moon, or of the Earth, Sun, and another planet is called syzygy. It is the Earth–Sun–Moon syzygy that causes spring tides.

Spring tides rise to a higher level than average and ebb to a lower level. The height of spring tides varies according to the accuracy of the Earth–Moon–Sun alignment; the more closely the three bodies are aligned, the higher the spring tides will be. Neap tides occur when lines drawn from the Sun and Moon meet in a right angle at the center of the Earth. The solar and lunar gravitational forces then act partly against each other, reducing the overall tidal effect. Neap tides are smaller than the average tides. As with the spring tides, their height varies according to the accuracy of the misalignment.

Although the two tidal bulges circle the Earth like waves, their magnitude and timing vary from place to place because of FRICTION between the waves and the ocean floor and because of the shape and orientation of coastlines. The amplitude of the waves (*see* WAVE CHARACTERISTICS) also varies with the volume of water through which it moves. Ocean tides are much larger than the tides in seas that are almost completely enclosed by land, such as the Mediterranean and Baltic Seas. The difference between the mean height of high and low water at a particular place is known as the tidal range.

The tidal range varies according to the phase of the Moon. Tidal range is greatest during spring tides and least during neap tides. Mean tidal ranges take account of these cyclical variations to provide a general value. Tidal range also varies according to the configuration of coastlines. Tides propagate as waves with a PERIOD similar to that of the forces generating the tides. When these sea waves arrive at coastlines or enter bays and estuaries, they may be reflected. The water may then form a standing wave, or seiche, with a period determined by the length and depth of the basin that contains it. If this period coincides with that of the tides, the amplitude of the tide can be increased greatly. That coincidence is the cause of the huge tidal range in the Bay of Fundy, in eastern Canada. The bay is about 168 miles (270 km) long, and its depth averages 230 feet (70 m). These dimensions mean the standing wave produced by the tide has a period of 12 hours, with the result that the tidal range at spring tides can exceed 50 feet (15 m). Elsewhere, tidal ranges are smaller. The mean tidal range at Boston, Massachusetts, is about 9 feet (2.7 m), for example. A tidal range of less than 6.5 ft (2 m) is called microtidal, one of 6.5–13 ft (2–4 m) is mesotidal, and one of more than 20 ft (6 m) is macrotidal.

Oceanic tidal movements play an important part in the transport of heat from the equator to polar regions. Tidal energy is dissipated in the deep oceans, and its dissipation causes some mixing of ocean waters. Some scientists now suspect that this mixing, combined with the wind-driven ocean currents, is more important than the THERMOHALINE CIRCULATION in the oceanic transport of heat.

Tides are also thought to be important in climate change. The declination of the Moon changes over a cycle that maximizes the tides every 1,800 years, and the amplitude of the cycle also varies over a cycle with a period of 5,000 years. Strong tides increase the amount of mixing in the oceans. Mixing with cold, deep water lowers the temperature of the surface water. Weak tides have the opposite effect. These cyclical variations coincide with, and may cause, abrupt fluctuations in climate that occur on much smaller timescales than the change between ice ages and INTERGLACIALS.

Very gradually, the tides are weakening. This is because the Moon is receding from the Earth by about 1.6 inches (4 cm) every year.

Titan atmosphere Titan is one of the moons of the planet Saturn, also known as Saturn IV. Its radius is 1,600 miles (2,575 km), mass 1.48×10^{20} tons ($1,345.5 \times 10^{20}$ kg), and mean density 117 pounds per cubic foot (1,881 kg/m^3). Titan is larger than Earth's moon, but much less dense. Titan was discovered in 1655, by the Dutch astronomer and physicist Christaan Huygens (1629–1695).

In 2004, the Cassini–Huygens space mission reached Titan, and on January 14, 2005, the Huygens lander descended through the Titanian atmosphere and landed on the surface. Huygens returned data and images during its descent and from the surface itself.

Titan has a thick atmosphere. The atmospheric pressure at the surface is 1.5 times that at Earth's surface, but the climate is much colder, with a mean surface temperature of -300 °F (90 K; -183°C). The northern hemisphere was found to be colder than the

An artist's impression of Saturn as it might appear to an observer on its satellite Titan. Titan's surface is made from rock and ice, and it has a thick atmosphere of nitrogen and organic compounds, mainly methane and ethane. Its atmosphere gives Titan its orange color. Scientists are interested in the atmosphere of Titan because it may be similar to the primitive atmosphere on Earth and contain the compounds from which life originated. ***(Chris Butler/Photo Researchers Ltd)***

southern hemisphere, but this may have been because Huygens landed during the northern-hemisphere winter.

The atmosphere consists mainly of NITROGEN, together with METHANE, ethane, and hydrogen cyanide. ULTRAVIOLET RADIATION and impacts by high-energy electrons dissociate atmospheric methane and drive chemical reactions that yield a range of other organic (carbon-based) compounds, principally acetylene, ethylene, ethane, and diacetylene. The methane must be constantly replenished, but its source is still unknown.

It is likely that methane condenses in the atmosphere and falls to the surface as rain. Every few centuries it is possible that Titan experiences a "methane monsoon" lasting for several months. During this time the PRECIPITATION would be intense.

Titan has a well-defined stratosphere and mesosphere. The tropopause is at about 30 miles (50 km), and the stratopause at about 186 miles (300 km).

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Tonian The Tonian was the earliest period of the NEOPROTEROZOIC era of the Earth's history. It began 1,000 million years ago and ended 850 million years ago. During the Tonian, the continents were probably joined together in the supercontinent Rodinia. The equator passed through the center of Rodinia, with East Antarctica, Siberia, Australia, and India in the Northern Hemisphere, and Congo, Amazonia, West Africa, and northwestern Europe (called Baltica) in the Southern Hemisphere. North America and the rest of Eurasia, together known as Laurentia, formed the central part of the supercontinent. Rodinia began to break apart about 900 million years ago, toward the end of the Tonian.

Single-celled aquatic organisms were the principal forms of life during the Tonian. Multicellular organisms may have appeared toward the end of the period. *See* APPENDIX V; GEOLOGIC TIMESCALE.

Topex/Poseidon A joint mission by NASA and the Centre National d'Études Spatiales (CNES) in France that used an ALTIMETER mounted on a satellite to measure the height of the surface of the ocean with unprecedented accuracy. The satellite, Topex, was launched from Kourou, French Guiana, in August 1992 on a Poseidon rocket. Topex orbited at a height of 830 miles (1,336 km) on a track with an INCLINATION of 66° and an orbital period of 112 minutes. It carried two altimeters, one built by NASA and the other by CNES. Both instruments measured the height of the ocean at the same points at intervals of 10 days.

The resulting data was distributed to scientists in nine countries, who used them in connection with other research programs investigating the global climate. The measurements showed changes caused by meanders in strong ocean currents, local vortices, and large eddies associated with BOUNDARY CURRENTS and subtropical GYRES. The data helped in forecasting and tracking TROPICAL CYCLONES, forecasting ENSO events, and in other aspects of ocean and climate research of value to offshore industries, shipping, fisheries management, and marine mammal research.

In January 2006, after completing 62,000 orbits of Earth, the Topex spacecraft lost its ability to maneuver and its mission came to an end.

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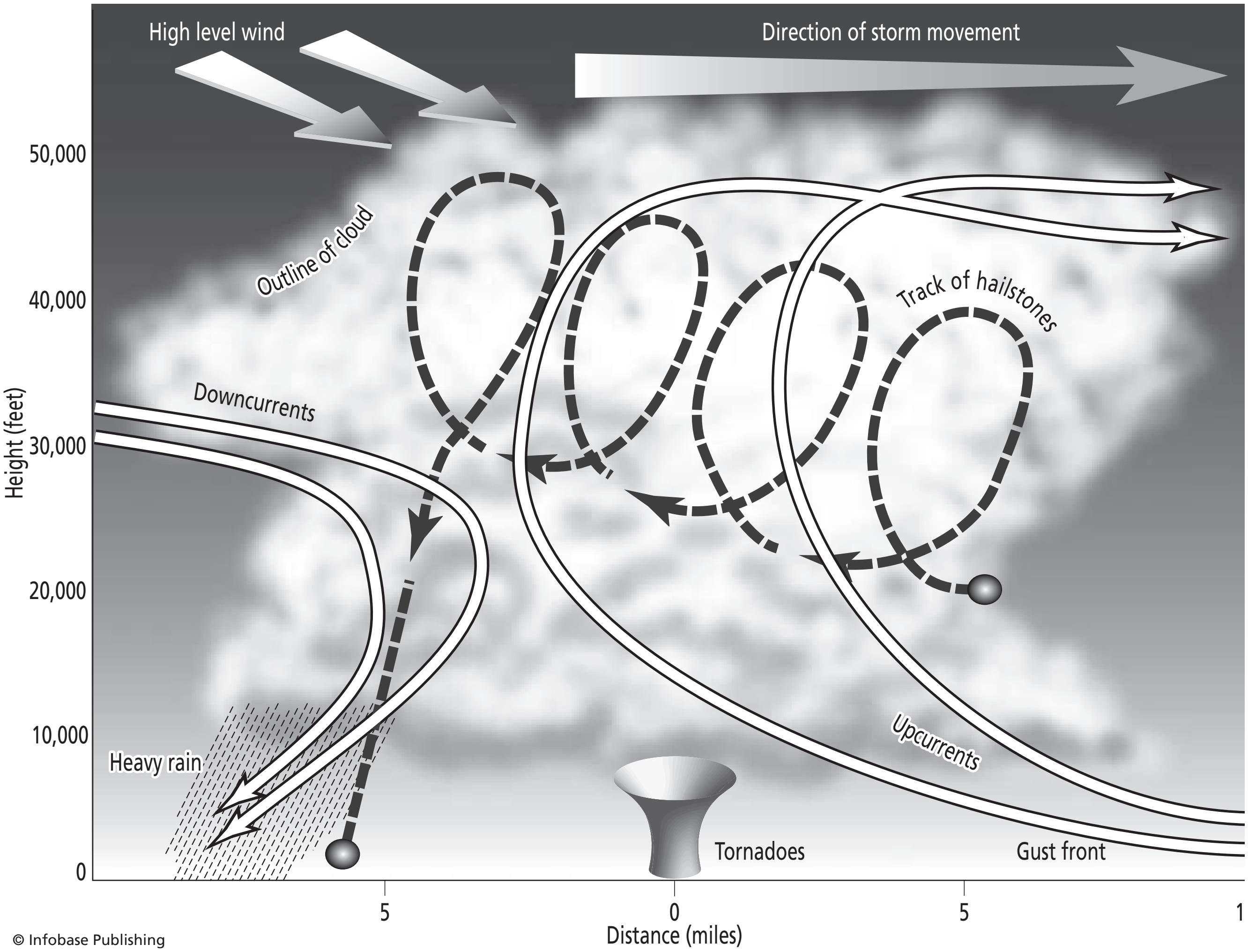
tornado (1) The most violent of all weather phenomena, a tornado develops inside a huge cumulonimbus storm cloud (*see* CLOUD TYPES), extends from its base, and produces winds that in extreme cases can reach 300 MPH (480 km/h). A storm that is capable of generating tornadoes is described as tornadic. Tornadic storms are sometimes isolated, but they are more likely to occur along a SQUALL line.

The storm cloud extends from below 1,000 feet (300 m) all the way to the tropopause (*see* ATMOSPHERIC STRUCTURE), at an average height of 50,000 feet (15.25 km), or even higher, penetrating the lower stratosphere. Inside the cloud the air is extremely unstable (*see* STABILITY OF AIR). As rising air cools, its WATER VAPOR starts to condense, releasing LATENT HEAT. The latent heat warms the air and makes it continue rising.



A cross section through a storm cloud that is producing a tornado. Ahead of the cloud there is a gust front, with strong winds, and at the rear of the cloud, behind the tornado, there are hail and heavy rain. The storm is driven by fierce air currents.

At the top of the cloud, rising air cannot penetrate far into the stable air of the stratosphere, and it spreads horizontally, forming an extension shaped like a blacksmith's anvil. The more vigorous the vertical air currents in the cloud, the bigger the anvil will be. The anvil extends at an angle of about 45° to the direction in which the storm is moving. In the Northern Hemisphere, the anvil extends to the left of the direction of motion as seen from above; in the Southern Hemisphere, it extends to the right.

Near the top of the cloud the air is very cold. The cold air sinks, warming adiabatically (*see* ADIABAT) and collecting moisture as it does so. This convective movement forms a number of cells (*see* CONVECTION). Ordinarily, the downcurrents in one cell interfere with the upcurrents in the neighboring cell, eventually suppressing them. When this happens, the storm dies. If the anvil is big enough, however, the upcurrents are swept clear of the downcurrents and a SUPERCELL forms, greatly extending the lifetime of the cloud.

Hemispherical protrusions called mammatus often form on the underside of the anvil of isolated tornadic storm clouds, but rarely on those along squall lines. At this stage of the storm's development, air is being drawn into the base of the cloud along its leading edge, so that strong GUSTS of wind blow toward the cloud as it approaches. This is the gust front. Air rises to the top and spreads into the anvil. Behind the anvil, equally strong downcurrents, producing first HAIL and then torrential rain as the storm passes, emerge as winds of up to hurricane force (more than 75 MPH, 120 km/h) from the rear of the cloud.

Small tornadoes sometimes form in the gust front. A tornado of this kind is called a gustnado. Because they spin in diverging air (*see* STREAMLINE), gustnadoes often rotate anticyclonically (clockwise in the Northern Hemisphere), unlike most tornadoes, which rotate cyclonically (counterclockwise in the Northern Hemisphere).

WIND SHEAR deflects the upcurrent at about the mid-height of the cloud. This causes the rising air to rotate about its own axis (*see* VORTICITY), creating a VORTEX with very low pressure at its center. The rotating air constitutes a MESOCYCLONE, and its rotation begins to extend downward through the cloud. As the mesocyclone grows downward, so its diameter decreases. The conservation of its angular MOMENTUM causes the wind speed to accelerate around the vortex.

Some tornadoes develop in relatively weak cumulonimbus clouds that contain no mesocyclone or supercell, and in which air is not rising vigorously. These are known as landspouts or nonsupercell tornadoes. Landspouts have been observed and the lack of a mesocyclone confirmed by Doppler RADAR. Wind shear inside the cloud sets the air rotating, but without developing into a mesocyclone.

Fragments at the base of the cloud start to rotate. Then part of the cloud base—in fact the bottom part of the mesocyclone where a mesocyclone exists—descends below the main cloud base, rotating slowly, to become what is known as the wall cloud. A funnel cloud, consisting of a rapidly spinning upcurrent, may emerge through the base of the wall cloud. If the funnel touches the ground, it will become a tornado, or twister, which is their popular name.

The funnel consists only of air, and it may be invisible. Most funnel clouds are visible, however, because moisture condenses in the relatively low pressure inside the vortex. The funnel looks as though it is an extension of the cloud; in fact it is a cloud in its own right, produced by condensation in the air being drawn into the updraft. When it touches the ground, the tornado funnel darkens because of the dust, debris, and other material that is swept into it and carried upward, and a cloud of dust and debris forms around its base.

A small column of spinning air may develop, rotating about its own axis and also moving in a circle around the main vortex of the tornado. This is called a suction vortex, and a major tornado may generate two or more suction vortices. Suction vortices are often hidden in the dust cloud that surrounds the base of the tornado, but they are responsible for many of the freakish effects a tornado sometimes produces. A suction vortex has been known to destroy half of a house, but leave the other half unscathed and vanish before it reached the house next door. Suction vortices may spin in either direction, but one that rotates in the same clockwise direction as the main tornado will generate winds up to 50 percent more powerful than those around the core of the main tornado. This is because the angular

Raining rats during a particularly violent storm; from *Der Wunderreiche Überzug unserer Nider-Welt* by Erasmus Francisci, published in 1680. *(Historic NWS Collection)*

Tornadoes can produce freak effects. On May 27, 1896, a tornado at St. Louis, Missouri, hurled this shovel with so much force it penetrated 6 inches (15 cm) into the tree. The picture is from "The New Air World," by Willis Luther Moore, published in 1922. *(Historic NWS Collection)*

VELOCITY of the suction vortex is added to the angular velocity of the main tornado and its mesocyclone, and also to the forward speed with which the tornado is moving over the ground. A tornado with winds of 200 MPH (322 km/h) may be surrounded with suction vortices spinning at 300 MPH (483 km/h).

Few suction vortices are more than 100 feet (30 m) in diameter, and some are no more than 10 feet (3 m) across. They are very short-lived. Few last longer than about three minutes, and few survive for long enough to complete even one full orbit of the main tornado.

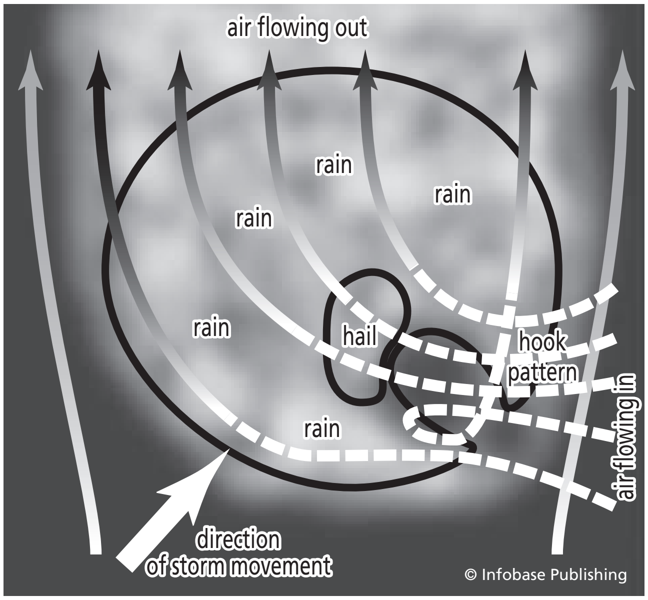
A suction vortex may leave its mark on open ground in the form of an approximately circular, shallow depression a few feet across called a suction scar. As it passes, the intense updraft of the suction vortex draws in loose dirt that is scattered from the top of the vortex. The vortex is so short-lived that hardly has it made its scar before it dies down. At one time, some people believed suction scars were the footprints of giants.

Tornadoes can happen anywhere in the world outside the TROPICS and at any time of year, but they are most common in the Great Plains of the United States. There their frequency is greatest between May and September, and they are most likely between 2 P.M. and 8 P.M.

When one develops, there may be more, occasionally many more. A chain of 148 tornadoes that occurred on April 3 and 4, 1974, became known as the Super Outbreak. Those tornadoes were produced by three separate squall lines that developed simultaneously and moved eastward. Together they extended from the southern shore of Lake Michigan to Alabama and at one point from Canada to the Gulf of Mexico. More than 300 people were killed. In 2003, a total of 395 tornadoes touched down in the United States between May 1 and May 10. One of these tornadoes lifted up a farmhouse in Iowa and set it down again more than 30 feet (9 m) away. Two of its three teenage occupants were unharmed, and the third boy suffered scratches from broken glass.

Most tornadoes die before they have traveled very far, but there are exceptions. The Tri-State outbreak in March 1925, so-called because it crossed Missouri, Illinois, and Indiana, included one tornado that traveled 219 miles (352 km) at an average speed of 60 MPH

Tornadoes are not always alone. Here two tornadoes are seen moving together through Elkhart, Indiana, on April 11 (Palm Sunday), 1965. *(Paul Huffman, Historic NWS Collection)*



A hook pattern is visible from above in the radar image of a cloud, indicating the imminent risk of tornadoes. The broken lines indicate air entering the storm at low level and climbing. The solid lines indicate air at high level leaving the storm.

(96 km/h). In 1977, a tornado crossed Illinois and Indiana, covering a record 340 miles (547 km) in 7 hours 20 minutes.

Tornadoes are classified by the damage they cause according to the FUJITA TORNADO INTENSITY SCALE. WATERSPOUTS, WHIRLWINDS, DUST devils, and WATER DEVILS are related phenomena.

Tornadic storms can sometimes be identified by a distinctive shape called a hook pattern that is often visible in radar images, taken from directly above, of the clouds associated with a supercell storm. The hook pattern usually occurs at the edge of a mesocyclone, but it is not entirely reliable, since not all mesocyclones produce one and not all mesocyclones lead to tornadoes. Doppler RADAR provides more reliable information on conditions inside a storm cloud.

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tornado (2) A particular type of violent but brief thunderstorm that occurs in West Africa is also known as a tornado. A West African tornado does not develop a MESOCYCLONE leading to a narrow column of rapidly rotating air that may extend below the storm cloud, and consequently it bears no relation to the "twister" type of storm.

West African tornadoes are associated with the southwesterly MONSOON and air from the harmattan (*see* LOCAL WINDS). Near the coast they develop between March and May and in October and November, and they occur inland between May and September.

The storms lie along a SQUALL line, from 10 miles (16 km) sometimes to 200 miles (320 km) long in Nigeria. They travel from east to west at about 30 MPH (50 km/h) and produce huge, dark clouds, frequent LIGHTNING, DUST and winds of up to 80 MPH (130 km/h) inland, but only half of that near the coast, and torrential rain once the squalls have passed. A tornado may last as little as 15 minutes and rarely for longer than two hours.

Tornado Alley The area of the Great Plains, in the United States, where tornadoes occur more frequently than they do anywhere else in the world and where the most violent TORNADO outbreaks are experienced. Tornado Alley is centered on Texas, Oklahoma, and Nebraska, but the area also covers Kansas, Iowa, Arkansas, Missouri, Alabama, and Mississippi, and tornadoes are also fairly frequent in northern Florida. In all these states there is an average of five tornadoes every year.

This region suffers more than any other because of its geography and the AIR MASSES that affect it. When it reaches the North American coast, air that has crossed the North Pacific is cool and moist. This maritime air rises to cross the Rocky Mountains, losing much of its moisture as it does so. On the eastern side of the mountains it descends gently, warming slightly by compression, and advances slowly across the Great Plains behind a weak cold FRONT that is aligned approximately southwest to northeast.

At the same time, continental tropical air forms over Mexico, New Mexico, and Texas and moves northward. This air is warm and dry, and in spring and summer, when the land warms rapidly, it is heated further as it advances. It enters the plain as hot, dry air.

A third mass of air forms over the Gulf of Mexico. This air is warm and moist, and it moves in a northwesterly direction.

When the two air masses, from Mexico and the Gulf, meet over northern Mexico and the southern United States, the moist air from the Gulf is held beneath the less dense continental air. The two move northwestward, the lower air warming still more as it crosses the hot land surface. Small clouds form, but although the air is being warmed strongly from below, the warm air cannot rise very far by CONVECTION, because of the overlying layer of dry air, and the clouds bring very little rain.

On the western side of the Great Plains the two air masses meet the weak cold front advancing from the opposite direction. The cold air undercuts the warm air. There is now a "sandwich" of air, with dry air at the bottom and top and warm, moist air between them. The moist air is forced to rise as the cold air pushes beneath it. As it does so, it expands, cools, and its WATER VAPOR starts to condense. At the same time, its rate of cooling changes from the dry to the saturated LAPSE RATE. The air becomes very unstable (*see* STABILITY OF AIR) as it rises up the cold front. Eventually convection within it becomes so vigorous that upcurrents start to break through the overlying dry air. When that happens, the clouds rise all the way to the tropopause (*see* ATMOSPHERIC STRUCTURE) and often beyond it into the lower stratosphere.

It is these clouds that produce some of the most violent thunderstorms known, and because they form along the cold front, which is still moving in a southeasterly direction, they tend to link together in SQUALL lines. These are what produce the tornadoes that give Tornado Alley its name.

Tornado and Storm Research Organization A British organization, founded in 1974, that exists to gather data and undertake research into TORNADOES and other severe weather phenomena in Europe. It has representatives in Austria, France, Germany, Ireland, and Switzerland.

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torque (**couple, moment of a force**) Torque is a twisting force that is equal to the product of a force and its distance from a point about which it is causing rotation. It is measured in newton meters (Nm) or pound-force feet (lbf ft). Torque is the force that causes air to rotate about a vertical axis.

Totable Tornado Observatory (**TOTO**) TOTO is a package of instruments designed to survive the conditions inside a TORNADO with winds up to 200 MPH (322 km/h) and measure wind speed, atmospheric pressure, temperature, and electrical discharges. Its acronym, TOTO, refers to Dorothy's dog in *The Wonderful Wizard of Oz*.

TOTO was built in 1980, with limited funds and using spare parts, by Alfred L. Bedard and Carl Ramzy, scientists working at the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA) Environmental Research Laboratory in Boulder, Colorado. Weighing 400 pounds (182 kg), TOTO comprises a cylinder housed in a casing of half-inch aluminum set in a frame made from angle iron, with arms that hold the instruments extending from the casing. It is powered by batteries and records its measurements. Inside the cylinder there are strip-chart recorders connected to instruments that measure TEMPERATURE, AIR PRESSURE, WIND SPEED, and electrical discharges.

TOTO could be carried in the back of a pick-up truck and deployed within 30 seconds. It remained in use for many years, finally to be joined by the "Turtle," developed by University of Oklahoma meteorologist Fred Brock. The Turtle is smaller and lighter than TOTO, and it records data digitally. Its name refers to its appearance. Its instruments are housed inside a hemispherical metal shell.

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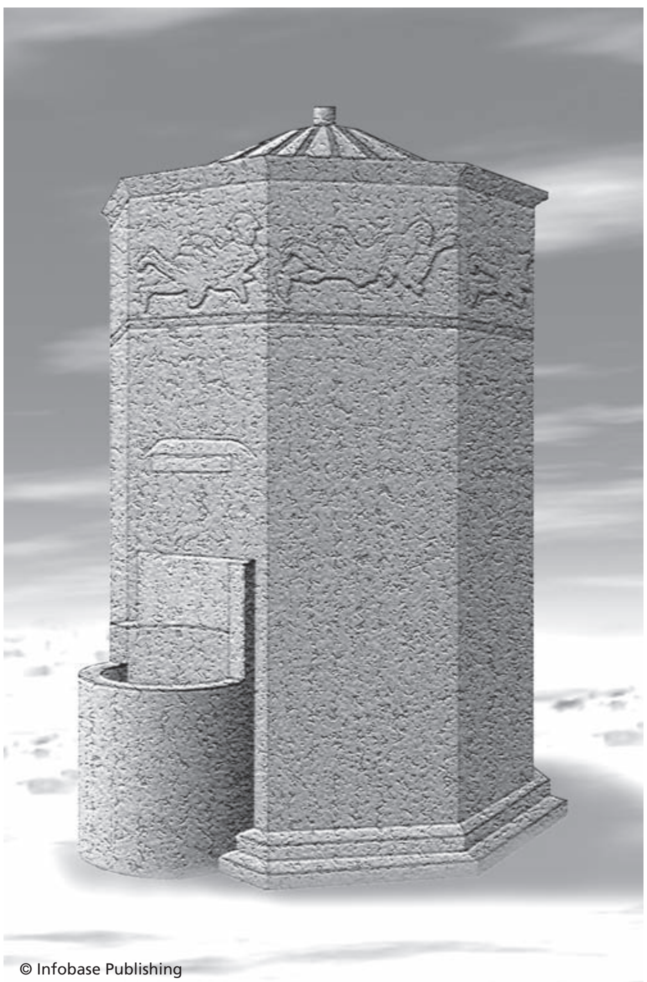
Tower of the Winds (**horologion**) The Tower of the Winds is believed to be the first device ever invented with the purpose of forecasting the weather. It was designed by the Greek astronomer Andronicus of Cyrrhus (who flourished around 100 B.C.E.) and was built in Athens at some time in the first century B.C.E. A substantial part of it is still standing.

The tower had eight sides. Figures representing the eight principal wind directions were carved at the top of each side. Boreas, the north wind, was portrayed as a man wearing a cloak and blowing through a twisted seashell. Kaikas, the northeast wind, was a man carrying a shield from which he poured small, round objects that were possibly hailstones. Apeliotes, the east wind, was a young man holding a cloak filled with grains and fruit. Euros, the southeast wind, was an old man wrapped in a cloak. Notos, the south wind, was a man emptying an urn to produce a shower of water. Lips, the southwest wind, was a boy pushing a ship. Zephyros, the west wind, was a young man carrying flowers. Skiron, the northwest wind, was a bearded man carrying a pot filled with charcoal and hot ashes.

On top of the tower there was originally the bronze figure of Triton with a rod in his hand. The Triton (in some stories there are several Tritons) was a mythological being with the head, trunk, and arms of a human and the lower body of a fish. He was the son of Poseidon, the god of the sea, and Amphitrite, daughter of Oceanos and Tethys. The Triton figure turned in the wind, indicating the wind direction. This statue gave rise to the custom of placing WIND VANES, often in the form of a weathercock or other figure, on the tops of church steeples.



Most of the octagonal Tower of the Winds is still standing. It was built in the first century C.E. and helped Athenians predict the weather (and tell the time).

Each side also had a sundial. As the Sun crossed the sky in the course of the day, at least one dial would always be showing the time. Thus, the tower was also a public timepiece. Even in Athens, however, the Sun does not always shine. To help people tell the time on cloudy days the tower contained a very elaborate clock driven by water (and called a clepsydra) that showed the hours on a dial.

In addition, the tower also had a disk that rotated, showing the movements of the constellations and the Sun's yearly course through them. Andronicus also built another tower with sundials around its sides, on the Greek island of Tenos.

The principle behind the weather forecast was simple. Traditionally, the Greeks had believed that their gods produced the weather. Make an appropriate offering to Zeus, father of the gods, and he would send good weather; please Poseidon, and he would send a storm to destroy your enemies. Aristotle (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), on the other hand, had maintained that the weather has entirely natural causes and that in principle it can be understood and even predicted. The fifth-century B.C.E. dramatist Aristophanes (*ca.* 450–*c.* 388 B.C.E.) wrote a play about the weather, called *Clouds,* that includes a debate between an educated philosopher and an unsophisticated person from the country over whether thunder is made by Zeus or whether it results from the collision between clouds.

It was the more scientific, Aristotelian attitude that underlay the tower. The direction of the wind hinted at the weather that would follow. Athenians could look at the tower, see the direction in which the Triton was pointing, and deduce from that what the weather would be like over the next few hours or days. To help them, the gods of the winds, depicted on the faces of the tower, were also associated with particular types of weather. Everyone would have known that Boreas, the north wind, was a rude fellow who found it hard to breathe gently and was quite unable to sigh. Zephyrus, the west wind, was gentle. The sweetness of his breath brought forth flowers. Notus, the south wind, was wet, his forehead covered by dark clouds. Euros, the southeast wind, needed his warm cloak because he would bring cold, dry weather. The significance of the winds, of course, was true only for Athens. In other parts of the world, or even of Europe, wind directions might have quite different connotations.

While they thought about the kind of weather they might expect, the Athenians could also check on the time. The Greek word *hōra* means time, *logos* means account, so a horologion is a timepiece, or clock.

transparency Transparency is the capacity of a medium for permitting radiation to pass through it with no significant SCATTERING or ABSORPTION. The transparency of the atmosphere is usually measured by its transmissivity (*see* SOLAR IRRADIANCE) when the Sun is at its zenith (and the PATH LENGTH is 1).

The property of being transparent to radiant heat is called diathermancy (the adjective is diathermous).

Turbidity is a reduction in the transparency of the atmosphere that is caused by HAZE or AIR POLLUTION.

transpiration Plants need WATER for four reasons. Water is the source of HYDROGEN for PHOTOSYNTHESIS. Mineral nutrients dissolve in water present in the soil and enter through the root in solution. Nutrients are transported in solution to all parts of the plant, and the sugars produced by photosynthesis are also carried in solution through the phloem tissue. It is water that fills plant cells and keeps them rigid. In hot weather the EVAPORATION of water from leaf surfaces takes LATENT HEAT from the leaf, thereby lowering its TEMPERATURE. If a plant is deprived of water, it wilts, and unless the supply of water is restored, it may die.

Plants obtain their water from the soil. Water travels through the stems along channels that form tissue called xylem, and it evaporates through the tiny pores in the leaves called STOMATA (the singular is stoma). A much smaller amount evaporates from pores in the stem called lenticels. The evaporation of water from its surfaces helps keep the plant cool in very hot weather. This loss of water from the plant is called transpiration, and the amount involved is large. For example, in summer, a silver birch tree (*Betula pendula*), with about 250,000 leaves, may transpire 95 gallons (360 liters) of water a day, and a full-grown oak tree (*Quercus* species) transpires up to 185 gallons (700 l) a day. A maple (*Acer* species) transpires about 53 gallons (200 liters) an hour. This is water that the plant takes from the ground and returns to the air. Not surprisingly, this transport of water dries the ground and increases the HUMIDITY of the air. It is one of the ways in which plants influence the climate.

If a plant stem is cut, liquid will seep from it. This liquid, called sap, is mainly water, and it is flowing upward. A small herb may lift water a few inches above the ground, but a Sierra redwood tree (*Sequoiadendron giganteum*) can grow to a height of 300 feet (90 m) and has roots that extend many feet to either side. The tree raises water all the way from its roots to the leaves on its topmost branches.

Transpiration is driven from the leaves and not from the ground; the water is pulled from above, not pushed from below. Beneath the surface cells with their stomata, leaves have a layer of tissue called mesophyll. The inside of mesophyll cells is coated in a film of water, and when the stomata are open some of this water evaporates. Hydrogen bonds (*see* CHEMICAL BONDS) between water molecules draw in more water to replace the water that has been lost. Adhesion and cohesion (*see* SOIL MOISTURE), processes which function in living tissues in just the same way as they do in the soil, then transmit this attraction all the way through the plant to the tips of its roots. There the attraction exerts a force that draws water toward the roots. The magnitude of this force varies from one plant species to another. In some it is very weak, but in others it can amount to more than 200 pounds per square inch (1,380 kPa), which is about 13.8 times sea-level atmospheric pressure. The force can be so strong that on a hot day, when the evaporation rate from the leaves is very high, water moves through the plant at up to 30 inches (76 cm) a minute and the sides of the xylem vessels are pulled in, making a measurable difference in the diameter of the stem.

It is possible to measure the rate of transpiration from individual plants under laboratory conditions, but extremely difficult to do so reliably outdoors. For practical purposes it is impossible to distinguish the WATER VAPOR entering the air by evaporation from exposed surfaces and that entering by transpiration. The two are therefore considered together, and the combined process is called EVAPOTRANSPIRATION.

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tree line The tree line is the climatic limit beyond which temperatures are too low to permit trees to grow. The tree line marks the boundary between tundra, with vegetation that includes small, stunted trees, and the bare rock, SNOW, and ICE of the high Arctic and Antarctic.

On mountains the height of the tree line varies with latitude and with the CONTINENTALITY OF OCEANICITY of the climate. The variation with latitude on a mountainside occurs because the tree line is determined by TEMPERATURE, and the temperature on a mountainside is determined by the environmental LAPSE RATE (ELR), so the temperature at any given elevation measured from a sea-level DATUM depends on the temperature at sea level. In the central Alps of Europe, for example, the tree line is at 6,500–7,000 feet (2,000–2,100 m), in the Rocky Mountains it is at about 12,500 feet (3,800 m), and in the mountains of New Guinea it is at 12,200–12,600 feet (3,700–3,800 m).

Usually trees will not grow where the mean summer temperature is lower than 50°F (10°C), so it is possible to calculate the approximate height of the tree line from the temperature at the foot of the mountain. Assume that the temperature at the tropopause (*see* ATMOSPHERIC STRUCTURE) is -74°F (-59°C) and the height of the tropopause is 36,000 feet (11 km). Subtract the temperature at the foot of the mountain from -74°F (-59°C) and divide the result by 36 (or 11) to give the ELR per 1,000 feet (or kilometer). Then calculate the height at which the temperature falls below 50°F (10°C). For example, the mean summer temperature in Seattle, Washington, is 71°F (22°C). Therefore:

$$-74 - 71 = 145$$

$$145 \div 36 = 4.03 \text{ (ELR)}$$

$$71 - 50 = 21$$

$$21 \div 4.03 = 5.2$$

If there were a mountain in Seattle, the tree line on it would be at a little over 5,200 feet (1.59 km).

tree rings The concentric rings that can be seen in a cross section of the trunk or large branch of a tree are called tree rings. The pattern of rings results from secondary growth.

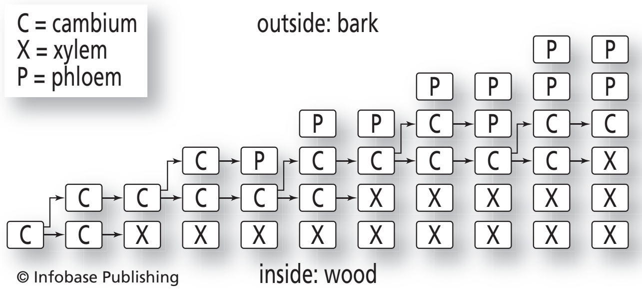
All plants, including trees, grow by extending the length of the main stem and branches. This is called primary growth. Woody plants such as trees and shrubs also grow thicker stems and branches. This thickening is called secondary growth, and it is secondary growth that produces the rings in woody plants.

The outside of a tree trunk is protected by bark. This is not simply a rough layer of dead tissue, however, but three layers, two of which are living. The rough outer layer consists of dead cells with a waxy coating. These are called cork cells, and they form the outer skin that protects the living cells beneath from injury and also keeps out water. Immediately beneath the cork cells there is a layer of living cells, called the cork cambium. These cells divide, but after a few weeks the cells die and become cork cells. A while later, the outer skin splits and more cork cambium cells are produced to fill the gaps, and then these also die and become cork cells in their turn. That is how the trunk acquires its rough surface.

Beneath the cork cambium, the innermost layer of the bark consists of tubular arrangements of cells composing tissue called phloem. Sugars produced in the leaves by PHOTOSYNTHESIS, are transported through the phloem to every part of the plant. If the bark of a tree is cut all the way around the trunk, sugars can no longer reach the roots because the phloem has been severed, and the tree will die. Cutting the bark in this way is called girdling or ring-barking.

There is another layer of cambium beneath the phloem. This is called the vascular cambium. It consists of cells that divide to produce more cambium cells, phloem cells, and xylem cells. Xylem cells also form a tubular system for transport, in this case to carry water upward from the roots to every part of the plant. Xylem and phloem tissues are composed of dead cells. Each time a cell of the vascular cambium divides into two, one of the new cells remains as a cambium cell and the other cell dies to become either a xylem cell or a phloem cell. Xylem cells accumulate on the inside of the vascular cambium. The resulting accumulation of xylem cells shifts the cambium layer progressively farther from the center of the trunk. This is the secondary growth that increases the thickness of the trunk and branches.

On the inside of the xylem, old cells fill with metabolic waste products, including the lignin that toughens



The history of a single cell in the vascular cambium. Each time the cell divides one of the resulting cells remains as a cambium cell and divided again, and the other dies to become either a phloem cell or a xylem cell.

cell walls. The inner part of the trunk or branch, consisting of dead tissue, makes up the heartwood, and the outer part, containing the active xylem and vascular cambium, is the sapwood.

In those parts of the world with a seasonal climate (*see* SEASONS), there is a period during which plant growth ceases. In temperate regions growth ceases in the winter, and in other parts of the world it ceases during the dry season, which may be the summer. The cessation is of both primary and secondary growth.

When the dormant period ends, the vascular cambium starts to produce new xylem tissue. The cells are large and have thin walls. They are a pale color. These cells form a cylinder surrounding the trunk or branch. Toward the end of the growing season—by late summer and fall in temperate regions—the vascular cambium produces xylem made from smaller, darker cells, with thicker walls. These form as another cylinder on the inside of the earlier xylem. When growth ceases for the year, the plant will have laid down two layers of xylem. In a cross section through the trunk or branch these will be visible as a pale, circular band and a narrower, dark band. Each pair of circles, or rings, marks one year's growth in the life of the plant. These are tree rings, and by counting them it is possible to determine the age of the tree.

Tree rings also reveal information about the conditions for plant growth during the year when they formed. If the weather was good, the rings will be broad, because growth was vigorous and many cells were produced. If the weather was poor, the rings will be narrow. If the weather was very bad, no growth at all may have occurred, and in this case one year's rings will be missing. Missing years can be detected only by cross-dating the rings from that tree with a standard reference compiled from many trees. The dating of wood by means of tree rings is called dendrochronology.

The possibility of dating material in this way was discovered in 1901 by Andrew Ellicott Douglass, an astronomer working at the Lowell Observatory, in Flagstaff, Arizona, who was interested in SUNSPOTS and who thought it might be possible to correlate tree rings with climate. Later, Douglass used the technique to date buildings in the prehistoric settlement of Pueblo Bonito, New Mexico, by matching tree rings from timber in the buildings with samples taken from trees of a known age.

The technique involves obtaining several samples that are first compared with each other to make certain no rings have been missed and there are no inconsistencies. If trees are being dated, the samples are also checked against specimens taken from other trees in the immediate vicinity and in the region. Finally, the tree rings are matched with an accepted reference standard. Using bristlecone pine rings from living trees and cross-dating them with rings from nearby dead trees, dendrochronologists can date material that is more than 8,200 years old.

Bristlecone pines are often used. These trees grow in the arid regions of California, and they survive to a remarkably old age. Some living specimens are 4,600 years old. There are two species, the Great Basin bristlecone pine (*Pinus longaeva*) and the mountain bristlecone pine (*P. aristata*). A complete chronology covering 5,500 years has been developed for one group of bristlecone pines. This chronology is used as a standard reference against which other tree-ring sequences can be calibrated. It is also used to calibrate RADIOCARBON DATING methods, by measuring the ratio of ^{12}C:^{14}C in individual rings and compiling a record of fluctuations in the ratio.

The relative widths of tree rings are indicative of general growing conditions year by year, but closer examination of the rings yields more detailed information. When water evaporates, water molecules containing the lighter OXYGEN isotope (^{16}O) vaporize more easily, so rainwater is enriched in ^{16}O, compared with the heavier isotope ^{18}O, or, to phrase it another way, rainwater is depleted in ^{18}O. The separation of isotopes is called Rayleigh distillation. Plant roots absorb rainwater, and oxygen from that water becomes incorporated in plant cells, including the cells produced by secondary growth. Consequently, Rayleigh distillation may leave a trace in the tree rings. This signal is especially strong when the rainfall is extremely heavy, as it is during a tropical cyclone, because the torrential downpours associated with such storms supplies tree roots with water strongly depleted in ^{18}O.

A team of scientists led by Claudia Mora, a geochemist at the University of Tennessee at Knoxville, has studied the oxygen isotope ratios in tree rings from longleaf pine (*P. palustris*) trees that have been preserved in water or swamps around Lake Louise, Georgia. Mora and her colleagues have found tree-ring evidence for the Great Hurricane that struck Cuba in 1780 and for a period of 40 years in the 17th and 18th centuries when it seems that not a single hurricane struck Georgia.

A mountain bristlecone pine (*Pinus aristata*) in Pike National Forest. Bristlecone pines are very long-lived, and their annual growth rings—obtained by drilling a narrow core from the trunk, not by felling the tree—are used as a standard reference against which other tree-ring sequences can be checked. *(USDA Forest Service, Rocky Mountain Region Archives)*

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Triassic The Triassic is the first period of the MESOZOIC era of the Earth’s history. It began 251 million years ago and ended 199.6 million years ago.

During the Triassic the supercontinent of Pangaea straddled the equator, surrounded by Panthalassa, the “world ocean.” No sooner had Pangaea formed, however, than rifts appeared between what were to become North America and Africa, and the supercontinent began to break apart. The climate everywhere was warm and generally dry, and the interior of Pangaea had an extremely arid climate.

Starfish and sea urchins are among the marine invertebrate animals that first appeared during the Triassic. The seas also contained ichthyosaurs and other marine reptiles as well as lungfish. On land there were new species of insects and the ancestors of the dinosaurs, called archosauromorphs, evolved. (*See* APPENDIX V: GEOLOGIC TIMESCALE.

Tropical Atmosphere Ocean (TAO) A monitoring network that uses an array of moored buoys positioned across the Pacific Ocean to gather data from the sea surface and sea-level atmosphere. The data are used to improve the understanding, detection, and prediction of ENSO events. The array took 10 years to assemble and was completed in 1994.

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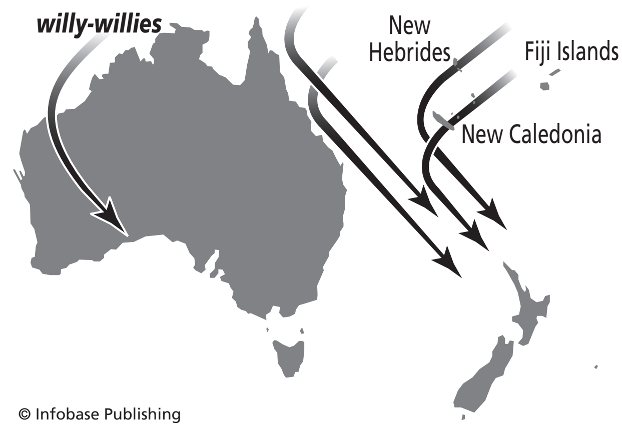
tropical cyclone A tropical cyclone is an area of low surface AIR PRESSURE that generates fierce winds and rain to become the biggest and most violent type of atmospheric disturbance experienced on Earth. TORNADOES often have greater wind speeds, but they are very local. Tropical cyclones affect a much larger area than tornadoes and contain storm clouds that often produce tornadoes.

Tropical cyclone is their scientific name, but these storms have several common names. In some parts of the Greater Antilles a tropical cyclone is known as a taino. Those that occur in the North Atlantic are called hurricanes, and that name is often applied to all tropical cyclones regardless of where they occur. Atlantic hurricanes move in a westerly direction, along a track that may carry them across several inhabited islands in the Caribbean. Then they turn onto a more northerly track that may carry them toward the United States, where they may make landfall along the Gulf coast, Florida, or the Carolinas. Many die while they are over land, but those that survive continue to turn until they are on an easterly track that carries them back over the Atlantic, occasionally as far as northwestern Europe, where they may still have enough strength to cause considerable damage.

Only one tropical cyclone has ever been recorded in the South Atlantic, because ordinarily the equatorial trough (*see* INTERTROPICAL CONVERGENCE ZONE) does not move far enough south of the equator over the Atlantic to provide the conditions they need. The solitary South Atlantic hurricane, called Catarina, occurred on March 22–28, 2005, near the coast of Brazil and caused considerable damage when it moved onshore. It attained only category 1 on the SAFFIR/SIMPSON HURRICANE SCALE. Meteorologists have not yet discovered how Catarina developed.

Tropical cyclones that occur in the North and South Pacific and the East China Sea and South China Sea are called typhoons. In the vicinity of Indonesia a tropical cyclone is known as a baguio, which is the name of a town in Luzon, Philippines, and near Australia it sometimes used to be called a willy-nilly or willy-willy. These storms develop in the Timor Sea, move southwestward and then swing to an easterly direction, a track that carries them toward the Australian coast. They are often very severe, but they die away as they move inland.

The coronazo de San Francisco is a tropical cyclone that forms over the eastern Pacific Ocean, off the coast of Central America between Costa Rica and Point Eugenio in Baja California, Mexico. The tracks of these storms usually carry them northward or northwestward



Tropical cyclones that strike northeastern Australia form over the Timor Sea. The map shows the direction in which they travel. They used to be called willy-willies or willy-nillies, but this name is no longer in use.

and many strike the coast. They are less violent than hurricanes that form over the Atlantic and Caribbean and they cover a smaller area. Those that form over the Bay of Bengal are called cyclones. Of all the tropical cyclones that occur, 90 percent are either cyclones or typhoons, and they are often extremely severe.

Tropical cyclones develop in or close to the equatorial trough around an area where the pressure is slightly lower than that of the surrounding air. This is called a tropical disturbance, and in the Atlantic it is often associated with an easterly wave.

An easterly wave, also called an African wave or tropical wave, is a long, weak, low-pressure TROUGH that moves from east to west across the tropical North Atlantic. It deflects the easterly trade winds, producing a wave pattern in the surface STREAMLINE. The wavelength (*see* WAVE CHARACTERISTICS) is usually 1,200–2,500 miles (1,900–4,020 km), and the waves travel about 6°–7° of longitude per day. Easterly waves last for 1–2 weeks before disappearing, and they are especially marked in the Caribbean region. In vertical profile the troughs producing easterly waves usually slope toward the east, so the weather associated with them occurs behind the line at which the trough lies on the surface. Ahead of the trough there is a RIDGE of high pressure, with generally fine weather, scattered cumulus cloud (*see* CLOUD TYPES), and some HAZE. Close to the line of the trough, the cumulus clouds are bigger, giving some showers, and improved VISIBILITY as the rain washes away the haze. Behind the trough, the wind veers, the temperature is lower, and the cloud thickens, with some cumulonimbus. SHOWERS are heavy, with some thunder. Easterly waves sometimes intensify to become tropical disturbances.

A tropical disturbance is an incipient tropical storm that is not associated with a frontal system. It is caused by the convergence of air at a low level. A disturbance may produce nothing more than single cumulus clouds that survive for only a few hours. The clouds are often aligned to form cloud streets (*see* CLOUD TYPES). More intense disturbances can produce much bigger clouds and SQUALL lines. If its central pressure falls, a tropical disturbance may develop into a tropical DEPRESSION.

Winds around a tropical depression blow at less than 38 MPH (61 km/h). If the depression deepens and these speeds increase, the depression is reclassified as a tropical storm.

A tropical storm is a tropical depression that has deepened until the winds around it are blowing at speeds of 38–74 MPH (61–119 km/h). When the mean wind speed exceeds 74 MPH (119 km/h), the storm is reclassified as a tropical cyclone. For purposes of identification tropical storms are given names, and these names are retained if they subsequently strengthen to become cyclones. Between 80 and 100 tropical storms develop in most years. Up to about half of those that survive long enough to cross an ocean develop into full cyclones.

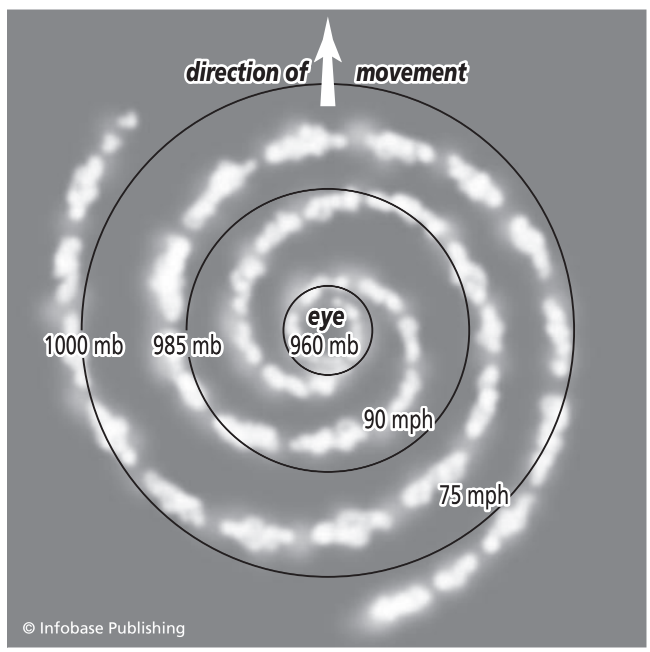
Air flows toward the low-pressure area. As it does so, the CORIOLIS EFFECT swings it to the right, and as it spirals into the low-pressure center it is accelerated by the conservation of its angular MOMENTUM. The air then spirals upward. The magnitude of the Coriolis effect is zero at the equator. A tropical cyclone cannot develop closer than latitude 5° north or south of the equator, because at that distance the Coriolis effect is too weak to set the air turning.

If the temperature of the sea surface is at least 80°F (27°C) over a large area, the rate of EVAPORATION will be high and the rising air will carry a large amount of WATER VAPOR. The rising air cools adiabatically (*see* ADIABAT), and as it does so its water vapor condenses, releasing LATENT HEAT. This warms the air, causing it to rise further, and towering cumulonimbus clouds form.

If the air rises vigorously enough, it will pierce the trade wind INVERSION. If the rising air is then able to flow into a high-level TROUGH, the upper-level low pressure will draw air upward, intensifying the low-level convergence of air (*see* STREAMLINE). A trough may be present in the upper troposphere (*see* ATMOSPHERIC STRUCTURE) as the remains of a weather system that has almost dissipated or as an easterly wave.

Three conditions must be met in order for a tropical cyclone to develop. The sea-surface temperature must be at least 80°F (27°C) over a large area. There must be an area of low pressure no closer to the equator than 5° north or south. There must be vertical WIND SHEAR at high level to accelerate the rising air. The second and third of these conditions may be met at any time of year, but the surface water reaches a high enough temperature only after it has warmed through the summer. It is then almost as warm as it is possible for the sea to become, because at this temperature the rate of evaporation is such that the latent heat of vaporization absorbed from the sea prevents the temperature rising higher. At the same time, wind across the surface mixes the warm surface water with cooler water below the surface. Consequently, there is a season for tropical cyclones. It begins in late summer and ends in late autumn, when the equatorial trough moves toward the equator and the sea starts to cool.

When fully developed, a tropical cyclone consists of a central eye surrounded by a solid bank of cumulonimbus clouds forming an eyewall, and then by several



The structure of a tropical cyclone, seen from above. The pale patches are clouds. Around the eye, the eyewall is the area of densest cloud, strongest wind, and heaviest rain. Pressures and wind speeds at various distances from the eye are indicated.

In the eye of Hurricane Debbie, August 20, 1969. Air is calm and warm in the eye, but the storm's fiercest winds occur near the surface in the wall of cloud surrounding the eye—the eyewall. ***(Edward E. Hindman, NOAA/AOML/Hurricane Research Division)***

concentric bands of cloud. The air is cool inside the eye of a tropical storm. There are clouds, some of which give precipitation. As the storm intensifies into a tropical cyclone, subsiding air in the eye is warmed adiabatically and becomes warmer than the air surrounding the eye. Meteorologically, it is the warm air in the eye that distinguishes a tropical cyclone from a tropical storm, rather than the increase in wind speed. In the eye the sky clears and conditions are calm, with a wind of no more than 10 MPH (16 km/h).

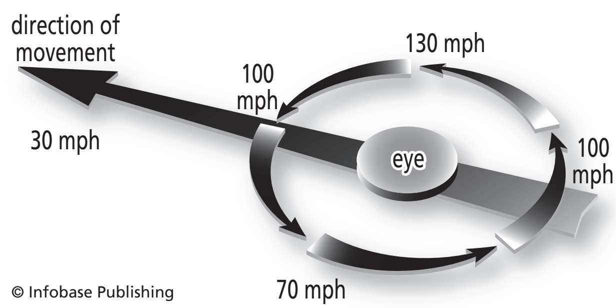
Convection in the eyewall is more intense than it is anywhere else in the storm, and it is in the eyewall that the strongest winds are generated and PRECIPITATION is heaviest. The eyewall consists of cumulonimbus cloud towering sometimes to 59,000 feet (18 km). Beyond this bank of cloud, in which air is rising vigorously, there is a region of clear skies and subsiding air, which is surrounded by a further bank of cumuliform cloud. There are usually several bands of cloud, the individual clouds becoming smaller with each band. The cyclone may extend to a diameter of up to 600 miles (965 km). Tropical cyclones are classified on the SAFFIR/SIMPSON SCALE of hurricane intensity according to the surface pressure in the eye and the wind speeds in the eyewall.

Low pressure in the eye causes the sea to rise. A fall in pressure of 1 millibar from the sea-level average of 1,013 mb produces a sea-level rise of 0.4 inch (1 cm). In the eye of a category 1 hurricane the sea level rises by about 14 inches (35.6 cm), and in a category 5 hurricane by about 40 inches (102 cm). The elevated sea level contributes to the severity of the storm surge that is produced as a tropical cyclone crosses a coast.

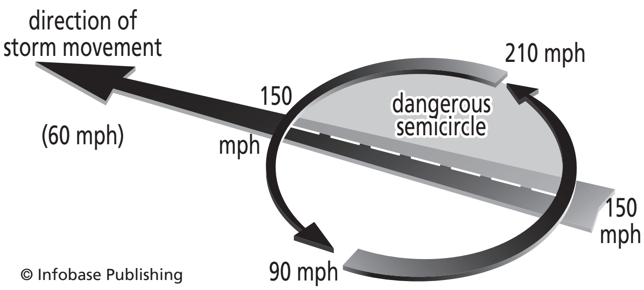
Tropical cyclones move in a westerly direction in both hemispheres, then turn away from the equator. In the case of hurricanes, this carries them into the Caribbean and, depending on where they turn northward, they may cross the coast of the United States, or miss it and remain over the sea. Those that remain over the sea for most of the time may travel all the way to Canada and even reach northwestern Europe, weakening all the time. Typically, tropical cyclones intensify as they start to move away from the equator, but they weaken rapidly once they leave the warm surface waters of the TROPICS.

Tropical cyclones travel initially at 10–15 MPH (16–24 km/h), but as they move away from the equator they accelerate, sometimes to double that speed. Because the entire system is moving, the wind speed on one side of the eye is greater than that on the opposite side. If the storm is moving at 30 MPH (50 km/h) and the wind speed in the eyewall is 100 MPH (160 km/h), then on one side the two speeds combine to produce winds of 130 MPH (210 km/h) and on the other side one speed must be subtracted from the other, producing winds of 70 MPH (110 km/h).

The side of a tropical cyclone where the winds are strongest and where they tend to push ships into the path of the approaching storm is called the dangerous semicircle. Because the circulation around the storm is cyclonic and the storms move in a generally easterly direction, driven by the trade winds (*see*



Wind speeds around the eye of a tropical cyclone vary as a result of the movement of the cyclone itself. On one side of the eye, the speed of the cyclone must be added to the wind speed, and on the other side it must be subtracted from it. In this example, the cyclone is traveling at 30 MPH (50 km/h) and the wind speed is 100 MPH (160 km/h). On one side of the eye, the actual wind speed is therefore 130 MPH (210 km/h), and on the other side it is 70 MPH (110 km/h).



The dangerous semicircle is on the northern side of a hurricane or typhoon in the Northern Hemisphere. If the storm is moving westward at 60 MPH (96 km/h) and generating winds of 150 MPH (241 km/h), in the dangerous semicircle the wind speed is 210 MPH (338 km/h) and blowing toward the storm track, pushing ships into the path of the storm.

WIND SYSTEMS), then turn away from the equator, the dangerous semicircle is on the side of the storm farthest from the equator. That is the northern side in the Northern Hemisphere and the southern side in the Southern Hemisphere. The other side, where the winds are lightest and where they tend to push ships out of the path of the approaching storm, is called the navigable semicircle. It is on the side of the storm closest to the equator. This is the southern side in the Northern Hemisphere and the northern side in the Southern Hemisphere.

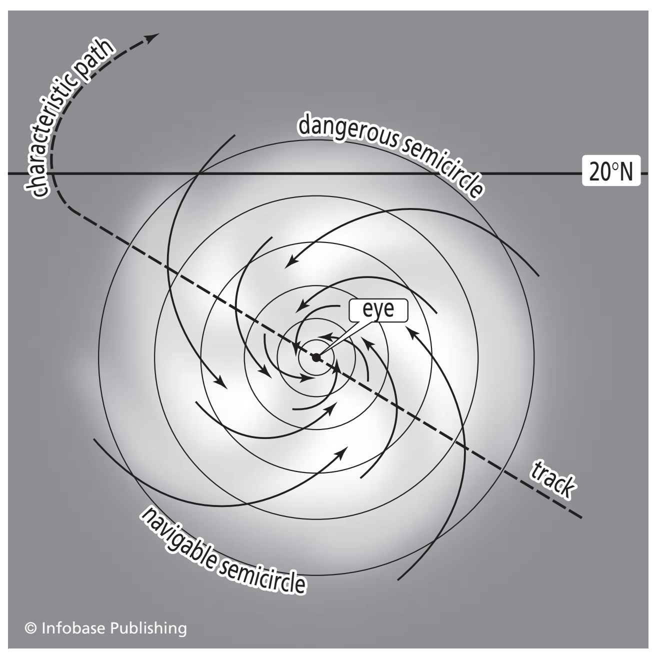
Pacific typhoons tend to be larger and more intense than Atlantic hurricanes, because they have a larger area of warm ocean over which to develop. Occasionally, though, they can grow much bigger. One that covers an area very much larger than the area covered by most is called a supertyphoon. A supertyphoon can be nearly 2,000 miles (3,200 km) across, with an area of 3 million square miles (8 million km^2). For comparison, the area of the United States is about 3.7 million square miles (9.5 million km^2). Fortunately, supertyphoons are very rare.

The Fujiwara effect is a phenomenon that occurs on average once every year and that was first described in 1921 by the Japanese meteorologist Sakuhei Fujiwara. If two typhoons of approximately similar size approach to within about 900 miles (1,450 km) of each other, they begin to interact. They start to turn about a point that lies about halfway between them. If one storm is much bigger than the other, they turn about a point that is closer to the larger storm. The big storm then absorbs the smaller one.

A tropical cyclone derives its energy from the condensation of water vapor, and therefore it retains its strength only for as long as it has an ample supply of warm water. As soon as it crosses land or sea water cooler than 80°F (27°C), the cyclone begins to weaken.

El Niño episodes (*see* ENSO) influence the number and intensity of tropical cyclones. During an El Niño there are fewer hurricanes in the Atlantic and Caribbean. The number of tropical cyclones remains unchanged on both sides of the equator in the western Pacific Ocean, but the storms tend to move farther east and into higher latitudes. There are more typhoons in the eastern Pacific, but fewer around Australia.

The number of tropical cyclones in a season also varies in a cycle of 20–30 years according to some scientists and 25–50 years according to others. From the 1970s until 1994, tropical cyclones were fairly uncommon. Their frequency increased in 1995. Between 1950 and 1990, there were an average of 9.3 tropical storms, 5.8 hurricanes, and 2.2 major hurricanes a year in the Atlantic. Between 1995 and 1999, there were an average 13 tropical storms, 8.2 hurricanes, and 4.0 major hurricanes a year. The number increased in the



On one side of a tropical cyclone, the wind blows in the opposite direction to the direction in which the storm is moving. This reduces the effective wind speed, and the winds tend to blow ships behind the center of the storm, rather than into its path. This is the navigable semicircle.

early years of the 21st century. In 2005, there were 26 named storms in the Atlantic and Caribbean, of which 14 were classed as hurricanes and 7 as intense hurricanes. Forecasters expect the increase to be maintained into the early decades of the 21st century. Overall, however, there has been no increase in either the frequency or severity of tropical cyclones since 1940, and between 1940 and 1990 the mean sustained wind speed decreased in hurricanes developing in the Atlantic Ocean and Caribbean Sea.

Some climate scientists believe that global warming could produce conditions that would lead to an increase in the frequency and intensity of tropical cyclones. Others accept that this is possible, but consider it unlikely.

The effect of hurricanes making landfall over the United States is related to the energy of each individual storm. Meteorologists at the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION calculate this from the hourly maximum sustained wind speeds over land from storms producing winds of at least the strength of a tropical storm. The resulting data, accumulated for a hurricane season, is then adjusted to make it compatible with similar data from storms at sea to produce an Accumulated Cyclone Energy (ACE) index. The ACE index allows hurricane seasons to be compared.

Meteorologists monitor the development and movement of tropical cyclones closely, using satellite images and data, data from ocean buoys, and reports from ships and aircraft. The buoys include specialized hurricane monitoring buoys. These are free-floating instrument packages that detect the approach of a tropical cyclone and are designed to be expendable. The hurricane rainband and intensity change experiment (RAINEX) is a three-year program funded by the U.S. National Science Foundation to study the dynamics of tropical cyclones. Using experimental models combined with data from aircraft carrying Doppler RADAR to examine turbulence and its effects, the aim is to improve the accuracy of forecasts of storm intensity. The WORLD METEOROLOGICAL ORGANIZATION sponsors research into the effects of tropical cyclones that cross coasts, through the International Tropical Cyclone Landfall Programme.

In the early 1960s, the U.S. government appointed a panel of scientific advisers to explore the possibility of bringing tropical cyclones under control. Project Stormfury comprised experiments to determine whether CLOUD SEEDING techniques would modify the condensation process sufficiently to rob a developing hurricane of its power by increasing rainfall in the first cloud band outside the eyewall and thereby slowing the development of the storm. Stormfury produced ambiguous results. Early in the 21st century another team of scientists, led by Ross N. Hoffman of Atmospheric and Environmental Research, at Lexington, Massachusetts, began using computer models to try other ways of modifying tropical cyclones. The model results suggested that in years to come it may become possible to deflect approaching storms, preventing them from making landfall.

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Tropical Ocean Global Atmosphere (**TOGA**) A program that ran from 1985 until 1994. It implemented an observational system for oceanic and atmospheric measurements with the aim of improving the understanding of ENSO events and, from that, their prediction. TOGA comprised satellite and surface measurements.

Tropical Prediction Center (TPC) The TPC is the part of the NATIONAL WEATHER SERVICE that issues watches and warnings about dangerous weather conditions in the TROPICS. The TPC is based at the campus of Florida International University, in Miami, and it is a component of the National Centers for Environmental Prediction. Under international agreement through the WORLD METEOROLOGICAL ORGANIZATION, the TPC has responsibility for generating and coordinating tropical cyclone forecasts for 24 countries in the Americas, Caribbean, and for the waters of the North Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and the eastern North Pacific Ocean.

The TPC has three branches. The NATIONAL HURRICANE CENTER (NHC) maintains a watch on TROPICAL

CYCLONES. The Tropical Analysis and Forecast Branch (TAFB) concentrates on forecasting, especially for ships and aircraft, and it interprets satellite data and provides satellite rainfall estimates. The TAFB also supports the NHC. The Technical Support Branch (TSB) provides assistance with the computer and communications systems.

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Tropics The Tropics are the two lines of latitude at which the Sun is directly overhead at noon on one of the two SOLSTICES. There is one tropic to each side of the equator, at latitudes 23.5°N and 23.5°S. The northern tropic is known as the tropic of Cancer and the southern is the tropic of Capricorn. Tropical regions (the Tropics) are those that lie between the two tropics.

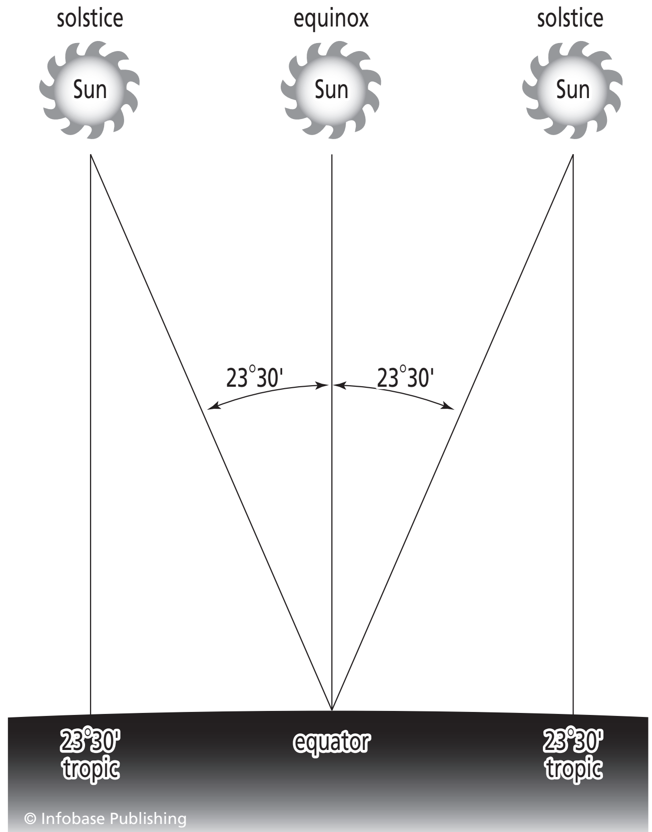
With respect to the PLANE OF THE ECLIPTIC, the rotational axis of the Earth is tilted 23.45° from the vertical (*see* AXIAL TILT). Because of this, in the course of its yearly orbit about the Sun, first one hemisphere and then the other is tilted toward the Sun. To an observer at the equator, the noonday Sun would be directly overhead at each EQUINOX, but at the solstices, in mid December and mid June, it would be approximately 23.5° to the south and north, respectively.

The belt around the Earth within which the mean annual temperature exceeds 68°F (20°C) is known as the hot belt.

tropophyte A plant that is adapted to a climate with pronounced wet and dry seasons.

trough A trough is a long, tonguelike protrusion of low AIR PRESSURE into an area of higher pressure. The waves in the polar front JET STREAM associated with the index cycle (*see* ZONAL INDEX) that extend toward the equator are also called troughs.

Trowal is a Canadian term for a trough of warm air that is held high above the surface by an OCCLUSION. It often produces layered clouds similar to those associated with a warm FRONT, and PRECIPITATION. As the trowal passes and cold air replaces it, the sky clears. Trowals are often shown on Canadian weather maps.



The Tropics are the regions on either side of the equator where the Sun is directly overhead at noon on at least one day every year. The Tropics are bounded by the tropics of Cancer and Capricorn, located at 23.5°N and 23.5°S, respectively. This latitude is also the angle between a point on the equator and the Sun when the Sun is overhead at one or other tropic, and the angle by which the rotational axis of the Earth is tilted with respect to the plane of the ecliptic.

A polar trough is a trough in the upper troposphere (*see* ATMOSPHERIC STRUCTURE) that extends toward the equator from the Arctic or Antarctic far enough to reach the TROPICS. The part of this high-level cold air that is closest to the equator sometimes becomes separated from the main part of the trough, to form a cutoff low (*see* CYCLONE) with a cold center. Air flows cyclonically (counterclockwise in the Northern Hemisphere) around the center, and if this flow extends to the surface, it will trigger a SUBTROPICAL CYCLONE.

A trough that forms at some distance from a major trough and that is related to it is called a resonance trough. The distance between a resonance trough and a dominant trough is measured in wavelengths (*see* WAVE CHARACTERISTICS) of ROSSBY WAVES. The trough that forms in winter over the Mediterranean Sea may be a resonance trough between the major troughs that lie above the eastern coasts of North America and Asia.

tsunami A tsunami is an ocean wave that is sometimes very large when it reaches the coast and that can cause great devastation. Unlike other waves, it is caused neither by wind nor by tidal movement—despite its old common name of tidal wave. The modern name, *tsunami,* is Japanese for "harbor wave," which is a much more accurate description.

Tsunamis are caused by major disturbances on the ocean floor. These include earth quakes, the eruption of submarine volcanoes, and large submarine mudslides that sometimes occur when sediments become unstable and slide down the outer edges of a continental shelf.

The tsunami that occurred on December 26, 2004, known in Asia as the Asian Tsunami and in other parts of the world as the Boxing Day Tsunami, resulted from a movement along the subduction zone where the Indian Plate is moving beneath the Burma Plate (*see* PLATE TECTONICS). Over a period of several minutes, approximately 750 miles (1,200 km) of the ocean floor aligned approximately north–south, rose by about 50 feet (15 m), causing an earthquake of about Richter magnitude 9.15 (the U.S. Geological Survey calculated 9.0 and other seismologists calculated 9.3). The earthquake hypocenter (the place where it happened) was about 100 miles (160 km) west of Sumatra, Indonesia, and 18.6 miles (30 km) below the seabed. The earthquake triggered tsunamis that sped across the Indian Ocean producing waves that in some places were 100 feet (30 m) high when they struck the coasts of Indonesia, Sri Lanka, India, and Thailand. In total the tsunami killed more than 280,000 persons.

A seabed disturbance of this kind sends a shock wave through the entire depth of ocean around it. This can be seen in war movies, where an explosion at depth causes a momentary shudder at the surface before the water displaced by the explosion is thrown into the air. A tsunami, therefore, is a shock wave transmitted through the ocean. Its wavelength and period are very long (*see* WAVE CHARACTERISTICS). Typically, a tsunami has a wavelength of about 160 miles (200 km) and a wave period of 15–20 minutes. Across the open sea tsunamis travel at a speed given by $\sqrt{(gd)}$, where g is the acceleration due to gravity (32 feet per second per second, or 9.81 m/s^2) and d is the depth of water. Because the average depth of the oceans is about 13,000 feet (4,000 m), a tsunami wave travels through the open ocean at an average speed of about 440 MPH (708 km/h). The wave is very small, however; its amplitude is rarely more than about 20 in. (50 cm). Two hours after the earthquake that triggered the Boxing Day Tsunami, RADAR instruments on satellites measured the wave crossing the ocean at a maximum of 2 feet (60 cm) high. The wave is so small, in fact, and it travels so fast, that out at sea sailors on ships often fail to notice it.

When the wave enters shallow coastal waters it slows down, because the wave speed is proportional to the depth of the water. Its wavelength shortens and its height increases, because water is still advancing toward the shore at the original wave speed, so water accumulates.

The size and form of tsunamis vary greatly, depending on the type, magnitude, and location of the disturbance that causes them and the configuration of the coasts they reach. Some appear as a breaker or a series of breakers. Others do not break as surf does, but resemble a rapidly rising TIDE that continues to rise until it has traveled far beyond the ordinary tidal limit. Often there is a warning of the impending approach of a tsunami. Water that is rising and falling against the shore with the normal movement of the waves retreats much farther than usual and remains for a few moments at a very low level. Then, when it advances, its advance takes it very much higher than usual. Anyone observing this phenomenon is well advised to seek safety immediately, by moving as quickly as possible to the highest ground within reach. They should not attempt to return to their homes until the emergency services tell them it is safe to do so.

Sensors maintain a constant watch for tsunamis in the Pacific Ocean, feeding data to centers in Alaska and Hawaii. No such warning system existed in the Indian Ocean at the time of the Boxing Day Tsunami, but one is being installed. Tsunami centers broadcast warnings to people living in a coastal area when a tsunami is approaching.

Further Reading

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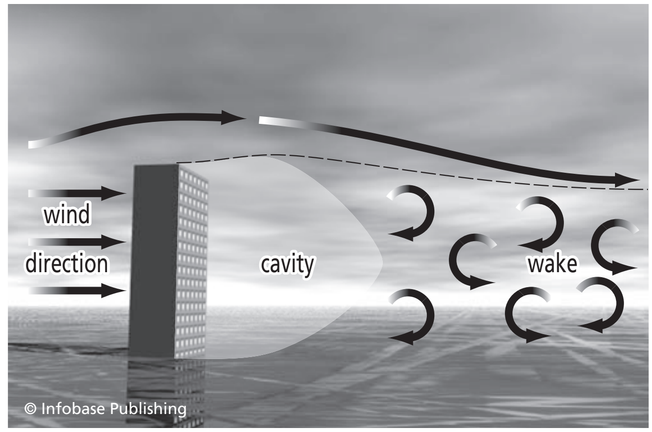
turbulent flow (**turbulence**) Turbulent flow occurs when elements of a moving fluid follow STREAMLINES that cross one another, so the flow passing any particular point changes speed and direction in an irregular and unpredictable fashion. Except in the laminar boundary layer (*see* LAMINAR FLOW) air movement is almost always turbulent.

The Richardson number is a mathematical value, devised by the English mathematician and meteorologist Lewis Fry Richardson (1881–1953; *see* APPENDIX I: BIOGRAPHICAL ENTRIES), that makes it possible to predict whether atmospheric turbulence is likely to increase or decrease. The Richardson number (*Ri*) is calculated from the strength of the WIND SHEAR, BUOYANCY of the air, and the POTENTIAL TEMPERATURE. It represents the ratio of the rate at which the KINETIC ENERGY of the turbulent motion is being dissipated by buoyancy due to natural or free CONVECTION to the rate at which kinetic energy is being produced by mechanical or forced convection. If *Ri* is greater than 0.25, turbulence will decrease and disappear. If *Ri* is less than 0.25, turbulence will increase.

Turbulent flow is the cause of the gustiness (*see* GUST) and the continually changing speed and direction of the wind felt at ground level, but turbulent flow acts vertically as well as horizontally. Where two belts of air are moving at different speeds, air at the boundary between them can be set rotating in a vertical plane. Turbulent flow perpetuates itself, because erratic movement in one place jostles the adjacent air and sets it moving, and FRICTION, convective movement, and pressure differences are continually introducing new disturbances to the flow.

A turbulent flow is a flow of air or other fluid that is irregular, with many eddies.



Immediately downwind of a building, there is a region called the cavity, and beyond that is the wake, a region of turbulence with erratic, gusty wind.

The range of frequencies of the oscillations that make up turbulent flow is called the spectrum of turbulence. In turbulent flow, air is moving at different local VELOCITIES that vary over different lengths and times. Variation in an oscillation over distance (wavelength) and time is a variation in frequency. The spectrum at a given point and in a given direction is the ROOT-MEAN-SQUARE velocity of the frequencies contributing to the motion for each bandwidth.

Turbulent flow produced in moving air that encounters physical obstacles, such as buildings or trees, is called mechanical turbulence. Mechanical turbulence causes EDDIES, with the result that close to the ground the wind may blow from almost any direction, especially in cities. It is why the wind direction must be measured in the open. A region of turbulent flow that lies downwind of a surface obstruction or behind a body that is moving through a fluid is known as a wake. The moving fluid passes over the surface of the object and becomes detached from the surface on the LEE side. The region where it becomes detached is called the cavity. The wake forms on the downwind side of the cavity. As the wind detaches, eddies form within the flow. These produce gusts of wind and rapidly changing wind directions in the wake of a building or other obstruction. If there is no further obstruction, the wake extends for a distance equal to about 10 times the height of the obstruction. The turbulent flow in the wake of a boat is clearly visible. The wake behind an aircraft is invisible, but it represents a serious hazard to any aircraft that enters it.

Local variations in TEMPERATURE and HUMIDITY that are produced by turbulent flow and that persist in the air after the movement that caused them has ceased and the DENSITY of the air has become uniform are known as fossil turbulence. Fossil turbulence scatters radio waves and can cause small clouds to form where air is made to rise.

U

ultraviolet index (**UVI**) The UV index is a guide to the intensity of ultraviolet radiation (*see* SOLAR SPECTRUM), reported as an index value that is related to the duration of exposure that will cause sunburn in the most susceptible people, which are those with pale skin. The index was developed by the U.S. Environmental Protection Agency and since June 1994 predicted UVI values for certain cities have been issued regularly by the NATIONAL WEATHER SERVICE. The index runs from 0 to 15, and the reported values are usually accompanied by recommended precautionary measures, which include the appropriate sun protection factor (SPF) for sunscreens.

The index is set out in the following table.

UV Index

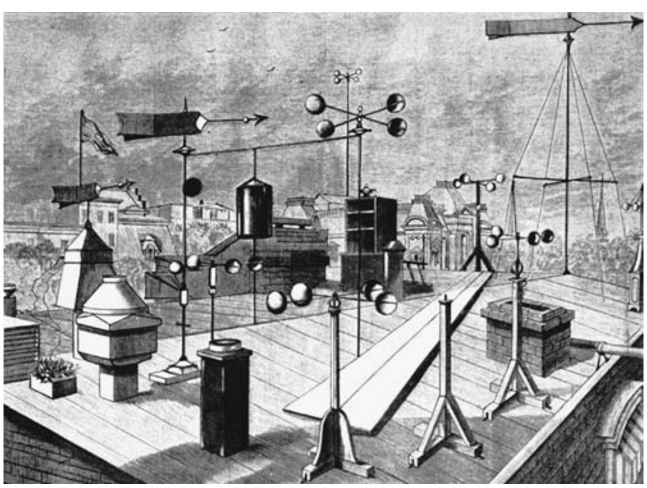
UV category	UVI value	Time to burn (minutes)	Precautions
Minimal	0–2	30–60	Wear a hat
Low	3–4	15–20	Wear a hat; use sunscreen SPF 15+
Moderate	5–6	10–12	Wear a hat; use sunscreen SPF 15+; keep in shade
High	7–9	7–8.5	Wear a hat; use sunscreen SPF 15+; keep in shade; stay indoors between 10 am and 4 pm
Very high	10–15	4–6	Stay indoors as much as possible; outdoors wear a hat and use sunscreen SPF 15+

United Nations Environment Programme (**UNEP**) A program established by the General Assembly of the United Nations in accordance with a resolution from the United Nations Conference on the Human Environment, which was held in June 1972 in Stockholm, Sweden. UNEP is charged with coordinating intergovernmental measures for the protection of the environment. Its headquarters are in Nairobi, Kenya.

In UN terminology, a program has a lower status than an agency. *See* EARTHWATCH PROGRAM, GLOBAL ENVIRONMENTAL MONITORING SYSTEM, GLOBAL ENVIRONMENT FACILITY, GLOBAL RESOURCE INFORMATION DATABASE, INTERGOVERNMENTAL PANEL ON CLIMATE

Change, Appendix V: Laws, Regulations, and International Agreements (Montreal Protocol on Substances that Deplete the Ozone Layer and Vienna Convention on the Protection of the Ozone Layer).

United States Weather Bureau The U.S. Weather Bureau is the federal agency that was instituted to gather meteorological data and to prepare and issue weather forecasts and warnings of severe weather. The inspiration to form the bureau was initially that of Thomas Jefferson (1743–1826), who had an abiding interest in meteorology and kept weather records over a number of years. In 1849 Joseph Henry (*see* Appendix I: Biographical Entries) inaugurated the collection of meteorological data at a central point, and on February 9, 1870, President Ulysses S. Grant signed a joint resolution of Congress that authorized the secretary of war to establish a weather service within the army. The Army Signal Corps operated the service until July 1, 1891, when the Weather Bureau was created as a civilian service within the Department of Agriculture. The bureau was transferred to the Department of Commerce on June 30, 1940; became part of the Environmental Science Services Administration on July 13, 1965; and in 1967 was renamed the National Weather Service.



Instruments for measuring wind deployed on the roof of the Headquarters Building of the Meteorological Service of the United States Signal Service. The picture is from a supplement to *Frank Leslie's Illustrated Newspaper,* published in New York on May 1, 1880. *(Historic NWS Collection)*

In 1898, the bureau started regular kite observations, which continued until 1933, and it began regular balloon soundings in 1909. From 1925, data were also collected by aircraft, and in 1926 the Air Commerce Act made the bureau responsible for providing weather services for aviation. Experiments with radio communication began in 1901, and in 1939 the bureau introduced the first telephone weather service, in New York City.

When the World Meteorological Organization was formed in 1951, the chief of the Weather Bureau, Francis W. Reichelderfer, was elected its first president.

Further Reading

National Weather Service. "NOAA History: A Science Odyssey." NOAA. Available online. URL: www.history.noaa.gov/legacy/nwshistory.html. Last updated April 21, 2004.

units of measurement Many units of measurement appear in books and articles on the atmospheric sciences. Most of these are SI units (*see* Appendix VIII: SI Units and Conversions), but not all of them are. The units in the following list are arranged in alphabetical order. Each unit is defined, and where appropriate the definition also explains how the unit acquired its name. Most of the units are metric and defined in relation to SI units ("SI units" is an abbreviation for Système International d'Unités).

Ampere (A) is the SI unit of electric current. It is equal to the constant current that, if maintained in two straight, perfectly cylindrical, parallel conductors of infinite length and negligible cross-section placed 1 meter apart in a vacuum would produce between the two conductors a force of 2×10^{-7} newton per meter of their length. The unit is named in honor of the French physicist and mathematician André-Marie Ampère (1775–1836).

Ångström (Å) is a unit of length that was formerly used to measure very small distances, such as those between molecules and the wavelengths of electromagnetic radiation. It was devised by the Swedish spectroscopist Anders Jonas Ångström (1814–74) and is equal to 10^{-10} m. It has been replaced by the SI unit the nanometer (1 Å = 0.1 nm).

Arcsecond is the unit in which very small angles are measured. It is equal to one-sixtieth of an arcminute, and 1/3,600th of a degree.

Atmosphere is a measurement of AIR PRESSURE. One standard atmosphere is equal to 0.101325 megapascals (MPa), 1.01325 × 10^5 newtons per square meter (N/m^2), or 1.013.25 bars.

Bar is a unit of pressure that is equal to 10^5 newtons per square meter (= 10^6 dynes/cm^2). The unit was introduced by Vilhelm Bjerknes (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) in *Dynamic Meteorology and Hydrography,* published in Washington in 1911. Meteorologists and climatologists now measure atmospheric pressure in pascals (1 Pa = 1 N/m^2), which is a much smaller unit (1 bar = 0.1 MPa), but weather reports and forecasts published in newspapers and broadcast on radio and TV still use the millibar (1 bar = 1,000 mb).

Becquerel (Bq) is the SI unit of radiation. It is equal to an average of one transition of a radionuclide (one decay) per second. The unit is named in honor of the French physicist who discovered radioactivity, Antoine-Henri Becquerel (1852–1908).

British thermal unit (Btu) is a unit of work, energy, or heat. The unit was first used by the English physicist James Prescott Joule (1818–89) in a paper on the relationship between heat and mechanical energy that he presented to a meeting of the British Association for the Advancement of Science in 1843. The unit was given its name in 1876. One British thermal unit is the energy that is required to raise the temperature of one pound of water through one degree Fahrenheit. This varies according to the starting temperature, and so this is sometimes specified. A mean value for the Btu is given by dividing by 180 the energy needed to raise the temperature of one pound of water from 32°F to 212°F (from freezing to boiling). This Btu is equal to 1055.79 joules. The accepted international value for the Btu is 1055.06 joules.

Bubnoff unit (B) is used to measure rates of EROSION. The unit is equal to the erosion of 1 micrometer (µm) of material per year. It was named for the German geologist Serge von Bubnoff (1888–1957).

Calorie (cal) is a C.G.S. unit of heat. It is equal to the amount of heat that is needed to raise the temperature of 1 gram of water by 1°C (= 1K). This value varies with the temperature of the water, however, so this had to be stated, with the result that there were eventually four separate calories in use. These were the International steam calorie (= 4.1868 J), the 15°C calorie (= 4.1855 J) which measured the heat needed to raise the temperature from 14.5°C to 15.5°C, the 4°C calorie (= 4.2045 J), from 3.5°C to 4.5°C, and the mean (0–100°C) calorie (= 4.1897 J). The unit was introduced in 1880. Except for the kilocalorie, or Calorie, equal to 1,000 calories, that is sometimes still used in reporting food-energy values, in 1950 the calorie was replaced by the SI unit the joule (J); 1 cal = 4.1868 J (based on the value of the International steam calorie).

Candela (cd) is the SI unit of luminous intensity, which is defined as the luminous intensity, measured perpendicularly, of a surface 1/600,000 m^2 in area of a BLACKBODY at the temperature of freezing platinum under a pressure of 101,325 pascals.

The c.g.s. system of units was introduced for scientific use before the SI system was developed. The c.g.s. system was based on the centimeter, gram, and second, but it proved unsatisfactory and confusing when applied to electrical quantities and heat measurements. Its use persisted for some time, but it has now been replaced by the SI system.

Coulomb (C) is the derived SI unit of quantity of electricity, or electric charge, which is defined as the charge that is transferred by a current of 1 ampere per second. The unit is named in honor of the French physicist Charles-Augustin de Coulomb (1736–1806).

Dobson unit (DU) is used to report the concentration of a gas which is present in the atmosphere or in a particular part of the atmosphere. It refers to the thickness of the layer that gas would form if all the other atmospheric gases were removed and the gas in question were brought to sea level and subjected to standard sea-level pressure. The amount of OZONE present in the stratospheric OZONE LAYER is usually reported in Dobson units. In the case of ozone, 1 Dobson unit corresponds to a thickness of 0.01 mm (0.0004 inch), and the amount of ozone in the ozone layer is typically 220–460 DU, corresponding to a layer 2.2–4.6 mm (0.09–0.18 inch) thick. The unit is named for Gordon Miller Bourne Dobson (1889–1976; *see* APPENDIX I: BIOGRAPHICAL ENTRIES), the British physicist who studied stratospheric ozone in the 1920s and who invented the DOBSON SPECTROPHOTOMETER.

Farad (F) is the derived SI unit of CAPACITANCE, which is defined as the capacitance of a capacitor that has a potential difference of 1 volt between its plates when it is charged with 1 coulomb. This is a very large unit and so the unit most commonly used is the microfarad (10^{-6} F). The unit is named in honor of the English chemist and physicist Michael Faraday (1791–1867).

Henry (H) is the derived SI unit of INDUCTANCE, which is equal to the inductance of a closed circuit that varies uniformly at one ampere per second and produces an electromotive force of one volt. The name of the unit was adopted in 1893 in honor of the American physicist Joseph Henry (1797–1878; *see* APPENDIX I; BIOGRAPHICAL ENTRIES).

Hertz (Hz) is the derived SI unit of frequency (*see* WAVE CHARACTERISTICS), which is equal to one cycle per second. The name of the unit was adopted in 1933, in honor of the German physicist Heinrich Rudolph Hertz (1857–94).

Joule (J) is the derived SI unit of energy, work, or quantity of heat. It is equal to the work that is done when a force of 1 newton moves a distance of 1 meter, or the energy that is expended by 1 watt in 1 second. The unit was adopted in 1889, and in 1948 it was adopted as the unit of heat. It is named in honor of the English physicist James Prescott Joule (1818–89).

Kelvin (K) is the SI unit of thermodynamic temperature, which is defined as being 1/273.16 of the triple point of water (*see* BOILING). 1 K = 1°C = 1.8°F. The unit is named in honor of the Scottish physicist and electrical engineer William Thomson, the first Baron Kelvin of Largs (1824–1907).

Kilogram (kg) is the SI unit of mass. It is equal to the mass of a prototype that is kept at the International Bureau of Weights and Measures at Sèvres, near Paris, France.

Knot is a unit of speed that was devised originally for use at sea, but that is also widely used by aircraft. It is a speed of one nautical mile per hour and, by international agreement, equal to 1.852 km/h. The United States adopted the international knot in 1954, but British ships and aircraft continue to use a knot equal to 1.00064 international knots. The knot came into use as a unit in the late 16th century. Then, the speed of a ship was measured by dropping over the side a float attached by a knotted rope. The knots were spaced 7 fathoms apart (a fathom is 6 feet, or 1.8 m) and the sailor measuring the speed counted the number of knots that passed in 30 seconds. This gave the speed of the ship in nautical miles per hour. Subsequently, the length of the nautical mile was changed, as was the distance between knots and the period of time used for counting, until the unit became standardized.

Langley (ly) is a unit of solar radiation that was suggested in 1942 by the German physicist F. Linke (in *Handbuch der Geophysik,* 8, 30) and named for S. P Langley (1834–1906; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). It is defined in the c.g.s. system as one calorie per square centimeter (using the 15°C calorie) per minute. The SOLAR CONSTANT is equal to 1.98 langleys.

Lumen (lm) is the derived SI unit of the rate of flow of light, known as luminous flux. It is equal to the rate at which light flows from a point emitting a uniform intensity of 1 candela in a solid angle of 1 steradian.

Lux (lx) is the derived SI unit of illuminance, which is the amount of light energy that reaches a unit area of surface in a unit of time. The lux is equal to the illuminance produced by a lumous flux of 1 lumen distributed uniformly over an area of 1 square meter.

Meter (m) is the SI unit of length. It is defined as a length equal to 1,650,763.73 wavelengths in vacuum corresponding to the transition of an atom of krypton-86 between levels $2p_{10}$ and $5d_5$.

Milli atmospheres centimeter (milli atm cm) is a unit used to measure volcanic emissions. It is identical in concept to the Dobson unit, in that it measures the quantity of a substance present in the air as the thickness of the layer that substance would form if it were the only constituent of the air and subjected to sea-level pressure. The atmospheric concentration of sulfur dioxide, for example, is usually about 15 milli atm cm. This means that if all the sulfur dioxide contained in the column of air from the measuring station to the top of the atmosphere were compressed into a layer of gas at sea-level pressure, that layer would usually be about 0.015 cm (0.006 inch) thick.

Millibar (mb) is the unit in which atmospheric pressure is commonly reported in weather forecasts. It is equal to one-thousandth of a bar.

Mole (mol) is the SI unit of amount of a substance. It is equal to the amount of any substance that contains as many elementary units as there are atoms in 0.012 kilogram of carbon-12. The elementary units may be atoms, molecules, IONS, electrons, or other particles or groups of particles, but they must be specified.

Nautical mile is a unit of length that was introduced early in the 17th century, based on a suggestion by the English mathematician and inventor Edmund Gunter (1581–1626). Gunter thought navigation at sea might be simplified if distances were related directly to degrees of latitude. To achieve this, he proposed establishing a unit of length that is equal to the distance subtended by one minute of arc. Consequently, one nautical mile is the average meridian length of one minute of latitude. That is, the length of one line of latitude divided by 21,600, which is the number of minutes of arc in 360°. It is necessary to take an average length, because the distance subtended by one arc minute of latitude varies slightly with latitude owing to the fact that the Earth is not perfectly spherical. The International Hydrographic Conference of 1929 recommended that this distance be measured at latitude 45°, to produce a nautical mile of 6,076 feet (1,852 m). This is the length that is most widely used. In Britain, however, the nautical mile is measured at latitude 48°, which gives a length of 6,080 feet (1,854 m), so that 1 English nautical mile = 1.00064 international nautical miles. A speed of 1 nautical mile per hour is known as 1 knot.

Newton (N) is the derived SI unit of force, which is equal to the force needed to accelerate a mass of 1 kilogram at 1 meter per second per second (1 N = 1 $kg/m/s^2$). The name of the unit was adopted in 1938 in honor of the English physicist and mathematician Sir Isaac Newton (1642–1727).

Ohm (Ω) is the derived SI unit of electrical resistance. It is defined as the resistance between two points in an electric conductor when applying a constant potential difference of 1 volt between them produces a current of 1 ampere in the conductor. It is the oldest of all the electrical units and was adopted in 1838. The unit is named in honor of the German physicist Georg Simon Ohm (1789–1854), and its symbol is the Greek letter omega (Ω).

Okta (octa) is a unit that is used to report the extent of cloud cover in eighths of the total sky; 1 okta = 1/8 of the sky covered by cloud. The CLOUD AMOUNT is measured by examining a reflection of the sky on a mirror marked out in a grid of 16 squares and counting the number of squares filled by cloud.

Pascal (Pa) is the derived SI unit of pressure, which is equal to 1 newton per square meter. The unit is named in honor of the French physicist, mathematician, and philosopher Blaise Pascal (1623–62; *see* APPENDIX I: BIOGRAPHICAL ENTRIES).

Radian (rad) is the supplementary SI unit of plane angle, which is the angle subtended at the center of a circle by an arc equal to the radius of that circle. If the radius is r, an arc of length r will subtend an angle of 1 rad and the circumference of the circle, $2\pi r$ will subtend an angle of $2\pi r \div r$ rad = 2π rad. The circumference subtends an angle of 360°, therefore 360° = 2π rad and 1 rad = 57.296°.

Second (s) is the SI unit of time. It is defined as the duration of 9,192,631,770 periods of the radiation that corresponds to the transition of an atom of caesium-133 between two hyperfine levels. The second is also a unit of angle (sometimes called an arcsecond), equal to 1/3,600 of a degree, and symbolized by ″.

Standard atmosphere (standard pressure) is a unit of pressure that is defined as a pressure of 1.013250×10^5 newtons per square meter (101.325 kPa, 1013.25 mb, 760 mm mercury, 29.9 inches of mercury, 14.7 lb/in^2). This is the average atmospheric pressure at mean sea level (sea level varies slightly from place to place). The definition assumes that the atmosphere consists of a perfect gas (a gas that obeys all the GAS LAWS) at a temperature of 59°F (15°C, or 188.16 K) and that the acceleration due to gravity is 9.80655 m/s^2. Sea-level pressure can be measured directly, but it is usually calculated from station pressures measured at known elevations above sea level. Unless it is stated otherwise, all reported atmospheric pressures are reduced to sea-level values. When reduced to a sea-level value, the pressure is called the reduced pressure (*see* BAROMETER).

Standard temperature and pressure (s.t.p.) are the conditions applied when measuring quantities that vary with temperature and pressure and especially when comparing the properties of gases. The conditions are a temperature of 273.15 K and pressure of 101,326 Pa.

Steradian (sr) is the supplementary SI unit of solid angle. It is defined as the angle, measured from the center of a sphere, that cuts off an area on the surface of the sphere equal that of a square with sides equal to the radius of the sphere.

Tesla (T) is the derived SI unit of magnetic flux density, which is the amount of magnetism per unit area of a magnetic field measured at right angles to the magnetic force. The tesla is equal to one weber per square meter (1 T = 1 Wb/m^2). The unit was adopted in 1954 and was named in honor of the Croatian-born American physicist and electrical engineer Nikola Tesla (1856–1943).

Torr is a unit of pressure equal to one millimeter of mercury. It is named after Evangelista Torricelli (1608–47; *see* APPENDIX I: BIOGRAPHICAL ENTRIES), and it was used for a time in some European countries, but is now little used. The tor, another unit named after Torricelli, and equal to one pascal, or one-hundredth of a millibar, was also proposed in 1913, but it, too, is rarely used.

Volt (V) is the derived SI unit of electromotive force, electric potential, or potential difference. It is defined as the potential difference between two points on an electric conductor that is carrying a constant current of 1 ampere and the power being dissipated between the two points is 1 watt. The unit was adopted internationally in 1881 and is named in honor of the Italian physicist, and inventor of the battery, Alessandro Giuseppe Anastasio, Count Volta (1745–1827).

Watt (W) is the derived SI unit of power, which is equal to 1 joule per second. The unit was adopted in 1889 and is named in honor of the Scottish engineer and instrument maker James Watt (1736–1819).

Weber (Wb) is the derived SI unit of magnetic flux, which is the amount of magnetism in a magnetic field calculated from the strength and extent of the field. The weber is equal to the magnetic flux that will produce an electromotive force of 1 volt in a conducting coil of one turn, as the flux is reduced to zero at a uniform rate in one second. The unit was adopted internationally in 1948 and is named in honor of the German physicist Wilhelm Eduard Weber (1804–1891).

Universal Time (UT) Universal time is a name for Greenwich Mean Time that was introduced in 1928, on the recommendation of the International Astronomical Union to avoid confusion. Universal Time is counted from midnight, but at the time of its introduction Greenwich Mean Time was counted from noon.

Greenwich Mean Time (GMT, Z) is the mean time, calculated from the position of the Sun, at the 0° meridian. The 0° meridian passes through Greenwich, England, which was formerly the site of the Royal Observatory. The 0° meridian was agreed at an international conference held in Washington, D.C., in 1884. At first, Greenwich Mean Time was calculated from noon. This was altered to midnight in 1925, but because of the possibility of confusion the name was changed to Universal Time in 1928.

Most time services that broadcast the time against which users may check their own clocks use coordinated Universal Time (UTC). UTC is based on the uniform atomic timescale.

Upper Atmosphere Research Satellite (UARS) The UARS is a NASA satellite that was launched on September 12, 1991. It carries six instruments that are designed to measure the TEMPERATURE, chemical composition, and WINDS in and above the stratosphere. These are the cryogenic limb array etalon spectrometer, improved stratospheric and mesospheric sounder, microwave limb sounder, HALOGEN OCCULTATION EXPERIMENT, high-resolution Doppler interferometer, and wind imaging interferometer (*see* SATELLITE INSTRUMENTS). Together, these instruments generate the most complete set of observational data for the upper atmosphere that have ever been produced.

Further Reading

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upwelling Upwelling is the name given to the rise of water all the way from near the ocean floor to the surface that occurs in particular regions of the ocean. Deep water is cold and, by bringing it to the surface, upwellings affect the temperature of the air in contact with the surface.

Upwellings are caused by the EKMAN SPIRAL. Ocean currents are driven by the wind, and they are subject to the CORIOLIS EFFECT (CorF). The balance between CorF and FRICTION between the wind and ocean surface produces two component forces of equal strength, one acting in the direction of the wind and the other acting at right angles to the wind direction. This results in the current flowing at an angle of 45° to the wind direction—to the right of the wind in the Northern Hemisphere and to the left in the Southern Hemisphere.

Below the surface the influence of the wind decreases, so the CorF becomes progressively more dominant with increasing depth. This has the effect of deflecting the current, and the overall result is that water in the surface boundary layer, down to about 82 feet (25 m), is slowly transported in a direction at right angles to the wind. Deeper water then rises to the surface to replace it. It is a slow movement, often at less than 3.3 feet (1 m) per day. The surface boundary layer that is subject to the Ekman spiral is known as the Ekman layer.

Where winds blow parallel to a north–south coastline and drive a current that flows near the coast and approximately parallel to it, the Ekman spiral pushes the water away from the coast, allowing deep water to rise to the surface. This is known as coastal upwelling, and it happens along the coasts forming the eastern margins of oceans, such as the western coast of North, Central, and South America. There, the ocean currents flow toward the equator—the California Current in the North Pacific and the Peru (or Humboldt) Current in the South Pacific. These carry cold water, but upwelling increases their cold influence. The difference is very marked. In August, the temperature of surface water in the Atlantic off the coast of North Carolina is often 70°F (21°C) and it can be warmer. The August temperature in the Pacific, in the same latitude off the coast of California, is about 59°F (15°C).

On either side of the equator the trade winds (*see* WIND SYSTEMS) drive currents from east to west in both hemispheres. Although it is very weak close to the equator, the CorF nevertheless acts on the Equatorial Currents, pushing them away from the equator. The result is that these currents are displaced a little way from the equator and there is a region of upwelling between them, the rising water dividing at the surface and flowing north and south. This is known as equatorial upwelling.

Upwelling, called open ocean upwelling, also occurs in the open ocean far from land. Atmospheric CYCLONES produce winds that drive currents. Like other currents, these are deflected by the CorF, and water rises to the surface layer. As a cyclone crosses the ocean, it leaves behind it a wake of relatively cool water. The deeper the cyclone the more pronounced this wake is, and it is very evident to the rear of a TROPICAL CYCLONE.

Ocean water is constantly turning over, but the process is extremely slow. The deep water that wells up to the surface was last at the surface centuries earlier (*see* GREAT CONVEYOR and NORTH ATLANTIC DEEP WATER). It sank in high latitudes and was very cold. Since the solubility of OXYGEN in water is inversely proportional to the temperature, the sinking water was rich in dissolved oxygen. It carried its oxygen to the ocean depths, where it sustained marine organisms. Inorganic nutrients, particularly nitrate (NO_3) and phosphate (PO_4), sink from the upper layers of the ocean and accumulate on the ocean floor. As it moves across the deep ocean floor, the deep water becomes enriched with these nutrients, and when it wells up to the surface, it brings them with it. This greatly enriches the ordinarily nutrient-poor surface waters, and upwellings support large marine populations. If the prevailing winds should fail, or change direction, the wind-driven current may also cease to flow, and without its movement the upwellings also cease. This is what happens during an El Niño (*see* ENSO). Its social as well as its meteorological effects can be serious. Fisheries that are sustained by the upwelling nutrients fail, and populations that are economically dependent on them suffer badly.

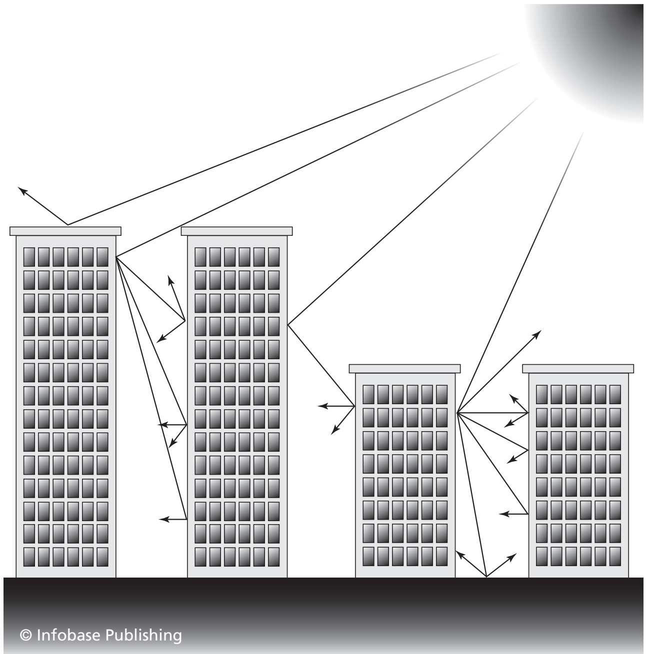
upwind Upwind is the direction from which the WIND is blowing. Wind direction always refers to the direction from which the wind blows, not the direction toward which it is blowing, so if the wind is a westerly, for example, the upwind direction is to the west. The opposite of upwind is downwind, meaning in the direction the wind is blowing.

urban climate Climatic conditions in a large city are markedly different from those in rural areas adjacent to that city. The difference between the two climates prevails throughout the year, so city dwellers experience a climate that is generally warmer, wetter, and less windy than the climate in which country dwellers live. The urban climate is a genuine phenomenon.

Various factors combine to make cities warmer than rural areas. A city is therefore an area of relative warmth surrounded by the cooler countryside, a phenomenon that is called the HEAT ISLAND effect. In winter, the city is an average 1.8–3.6°F (1–2°C) warmer than the surrounding countryside, and over the year it is 0.9–2.7°F (0.5–1.5°C) warmer. Because the city is warmer, there are 10 percent fewer heating DEGREE-DAYS in urban than in rural areas.

City air is also dustier, however. There are 10 times more small particles in urban air than there are in country air. High buildings also shade much of the ground surface. Between them these two factors reduce the amount of sunshine at street level by 15–30 percent. They also reduce the intensity of ultraviolet radiation (*see* SOLAR SPECTRUM) by 5 percent in summer and 30 percent in winter.

Warmer temperatures mean that the relative HUMIDITY is about 6 percent lower in the city. There is also less EVAPORATION, because surface water from PRECIPITATION is removed rapidly through storm drains, and less TRANSPIRATION, because there are fewer plants.



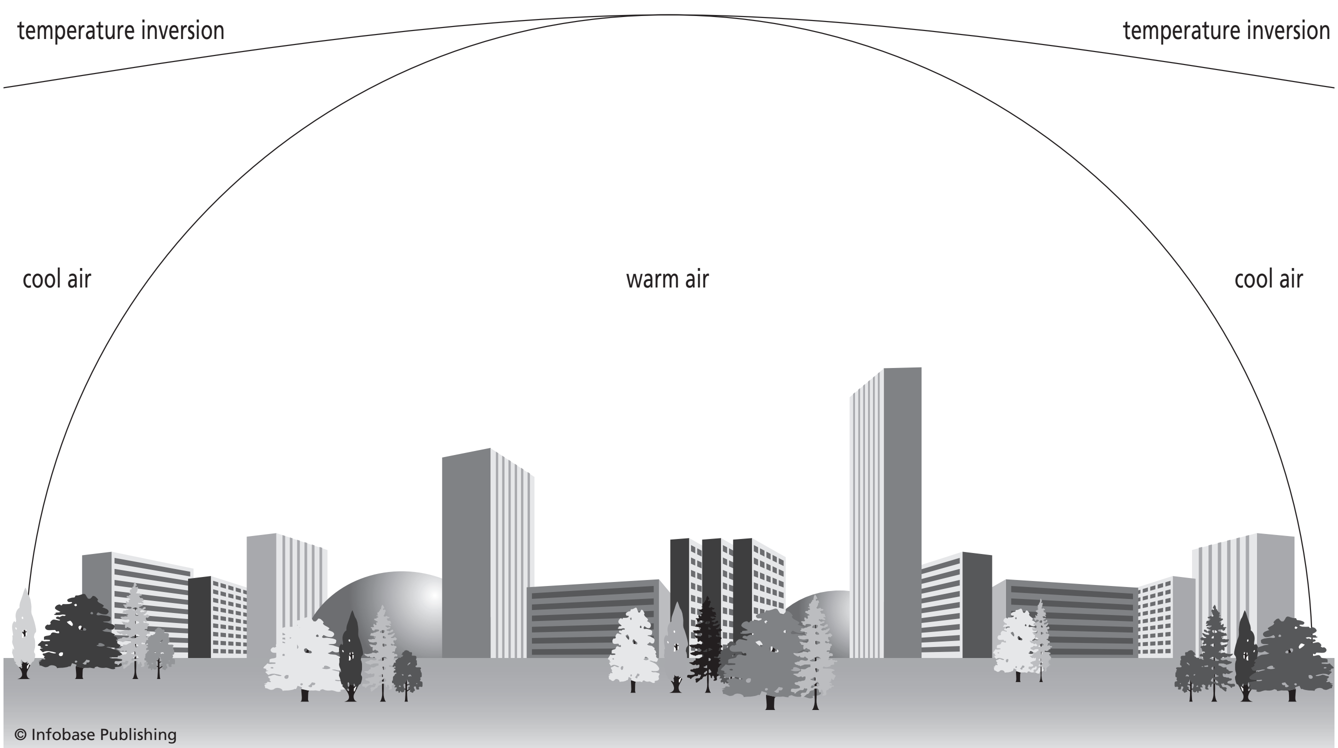
The pathways by which tall and short buildings reflect solar radiation. Little of the radiation reaches the ground. Almost all of it is absorbed by the fabric of the buildings.

The amount of precipitation over the city is 5–15 percent higher than it is in rural areas, however. This is probably due to the larger number of particles that are available as CLOUD CONDENSATION NUCLEI, although scientists are not yet sure. The city is 5–10 percent cloudier than the countryside. The warmer air increases instability (*see* STABILITY OF AIR) and the formation of cumuliform clouds (*see* CLOUD TYPES). Some of these develop into cumulonimbus, and cities experience 5 percent more THUNDERSTORMS than rural areas in winter and 29 percent more in summer.

Urban WIND SPEEDS are 25 percent lower than those in the countryside because of the effect of buildings, and there are 5–20 percent more days when the air is calm. At night there is often a country breeze (*see* WIND SYSTEMS).

A temperature INVERSION often forms above the city, especially in winter. This traps gaseous pollutants and particles, increasing the frequency of FOG. Fog occurs in winter twice as frequently in the city than in the countryside and 30 percent more often in summer.

The temperature inversion associated with an urban heat island encloses air inside what is called an



An urban dome forms when warm air rising over the city is trapped beneath an inversion. Air flows to the sides, cools, and returns to the ground, forming a domed shape

urban dome. Warm air rises over the city, encounters the inversion, and spreads to the sides. As it moves, it radiates away some of its own heat. This radiation cools the air, increasing its DENSITY, so the air subsides over the countryside just beyond the city boundary. From there it flows back into the city, toward the low-pressure region at the center. There is thus convergence in the inner part of the city and divergence above the city (*see* STREAMLINES), and the warm air beneath the inversion has an approximately domed shape. The urban dome is most pronounced on calm nights when the sky is clear, because that is when the heat island is most strongly developed.

Beneath the urban dome, the level of the rooftops resembles the canopy of a closed forest, and the layer of air below this canopy is called the urban canopy layer. The climate in this layer is strongly modified by the many microclimates (*see* CLIMATE CLASSIFICATION) produced by the streets and buildings. Winds blowing in from the surrounding countryside are slowed and deflected by the buildings and other obstructions they encounter, but they are also funneled (*see* WIND SPEED) along urban canyons. The burning of fossil fuels releases WATER VAPOR into the air, and some of the water piped into the city from outside evaporates. Together these modify the humidity of the air in the canopy layer. Its temperature is also modified by heat released from vehicle and other engines, industrial processes, and the air conditioning and heating of buildings. The magnitude of these effects changes in the course of the day, but it does so as a reflection of human activity rather than being wholly due to the daily cycle of sunshine and darkness.

A city street that is lined on both sides by tall buildings physically resembles a canyon. It is called an urban canyon. Wind tends to be funneled along the street, making it windier, especially if the street is aligned with the prevailing wind. The canyon also affects the way solar radiation is received and absorbed. Depending on the orientation of the canyon, the faces of buildings on one side may receive different amounts of radiation than those on the opposite side, or similar amounts but at different times of day. If the street runs north to south, for example, buildings on the western side will face the Sun in the morning and sunshine will reach buildings on the eastern side in the afternoon. If the street runs east and west, both sides will receive the same amount of sunshine through the course of the day, but protrusions from the buildings will cast deep shadows.

There is a rural boundary layer of air in the rural area adjacent to a large city. The boundary layer lies between the top of tall vegetation and the uppermost limit of the region within which the climatic properties of the air are modified by the surface below. The rural boundary layer is markedly thinner than the nearby urban boundary layer. Air in it is stable and capped by an inversion. Air moving outward from the city is carried above it, so the urban and rural bodies of air do not mix.

The urban boundary layer extends from the top of the urban canopy to the uppermost limit of the region in which the climatic properties of the air are modified by the surface below. The urban surface is usually rougher, warmer, and often drier than that of the surrounding countryside. The roughness reduces wind speed and generates EDDIES, the resulting TURBULENT FLOW mixing the air. The slowing of the wind causes air to accumulate and expand upward, and the upward expansion is increased by CONVECTION due to the heat island effect. Vertical expansion of the air produces and maintains the shape of the urban dome, and during the day it raises the upper margin of the urban boundary layer until it approximately coincides with the top of the PLANETARY BOUNDARY LAYER. At night the urban boundary layer contracts to about one-fifth of its maximum daytime depth. This is because air in the planetary boundary layer is stable at night, which restricts vertical movement.

V

vapor A vapor is any gas, although in METEOROLOGY the word is often used to mean WATER VAPOR. A gas, or vapor, is a substance that fills any container in which it is confined, regardless of its quantity.

The GAS LAWS describe the relationships between the TEMPERATURE and volume of an ideal gas, and the pressure that the gas exerts on the walls of its container. Gas molecules move freely, and bounce when they collide with one another or with a solid surface.

When a vapor is cooled, its molecules lose energy and move more slowly. If it is cooled sufficiently, the molecules will join in temporary groups and occupy a volume that reflects the number of molecules present, at which point the vapor has condensed and become a liquid.

Any substance that vaporizes readily at temperatures ordinarily found near the surface is said to be volatile.

varves Varves are sequences of light and dark bands that are visible in vertical sections taken from the sediments on the beds of some glacial lakes. The word *varve* is derived from *varv,* which is the Swedish word for layer. The study of varves, called varve analysis, helps scientists to measure how long the lake has existed and to determine the rate at which climate changed in the past.

One varve comprises one light band and one dark band. Within each varve, the pale layer is thick and has a coarse texture and the dark layer is thin and fine-grained.

In spring and summer, WATER that has melted from a nearby GLACIER flows rapidly into the lake. The meltwater carries small pebbles, sand grains, silt particles, and particles of clay, discharging all of them into the lake water. The bigger particles quickly settle to the bottom, forming a thick, pale layer of pebbles, sand, and some bigger silt particles. In winter, the edge of the glacier and the surface of the lake both freeze and the supply of meltwater ceases. All of the large particles now lie on the lakebed, but much smaller particles, of silt and especially of clay, sink much more slowly. They continue to settle through the winter, forming the thin, fine-grained, dark layer.

Since one layer is formed in summer and the other in winter, it is possible to measure the age of the lake by counting the varves in the same way that TREE RINGS can be counted to determine the age of a tree. The technique for doing this was introduced in 1878 by the Swedish geologist Gerhard Jacob de Geer (1858–1943). By counting the varves in Scandinavian lakes, de Geer concluded that southern Sweden was still covered by ice 13,500 years ago. As temperatures rose, the glaciers retreated to the north, and then, 8,700 years ago, the glaciers separated into two small ice caps.

Varves also form in milder climates that allow aquatic algae (single-celled, plantlike organisms) to grow for part of the year. These varves comprise one layer that is rich in organic matter and one that contains little organic matter.

In summer, there is a bloom of algae, and as they die the remains of dead algae settle to the lakebed to form the organic-rich layer. At the end of the summer, the blooms die down, so the winter layer contains much less organic matter. That is how the Green River Formation developed over an area of 48,250 square miles (125,000 km^2) in southwestern Wyoming, northwestern Colorado, and northeastern Utah during the EOCENE epoch (55.8–33.9 million years ago).

Where the surface of the lake freezes in winter the process is a little different. The ice insulates the water from cold winds and also traps the heat that the water would otherwise lose by BLACKBODY radiation. Sunlight can penetrate the ice, however, and the algae continue to grow through the winter, albeit slowly. Their remains settle on the bottom, forming a thin, organic-rich layer. In spring, when the ice melts, water rushes into the lake carrying pebbles, silt, and sand. This mixes with the dead algae as it settles to the lakebed, so although the algae are growing more vigorously, the summer layer contains a smaller proportion of organic matter.

The thickness of varves provides an indication of the warmth of the weather during each year.

vector quantity A vector quantity is a physical amount that acts in a direction, so that its description must include both the magnitude of the amount and its direction of action. This is contrasted with a SCALAR QUANTITY.

VELOCITY is a vector quantity. Wind velocity is the speed of the wind and the direction from which it is blowing. The speed of the wind, which is a scalar quantity, can also be stated, omitting the direction.

velocity The velocity of a body is the speed at which that body is traveling in a specified direction. Speed is a scalar quantity, which means that only its amount is relevant and not the direction in which it acts. TEMPERATURE is also a scalar quantity. Velocity is a VECTOR QUANTITY, which means its direction of action must be specified.

It is correct, for example, to report the wind speed as, say, 25 MPH (40 km/h), but it would be incorrect to describe this as the wind velocity. The wind velocity might be 25 MPH from 240°, often abbreviated as 25/240, 240° being the compass direction from which the wind is blowing.

The speed of a body that is moving along a curved path is known as its angular velocity. Angular velocity is usually expressed in radians (*see* UNITS OF MEASUREMENT) per second (rad/s) and described by the symbol Ω. The circumference of a circle is equal to 2π radians. It follows, therefore, that $\Omega = 2\pi \div T$, where T is the time taken to complete one revolution. The tangential velocity (V)—the velocity in a straight line that can be measured in miles or kilometers per hour—is given by $V = \Omega r$, where r is the radius of the circle.

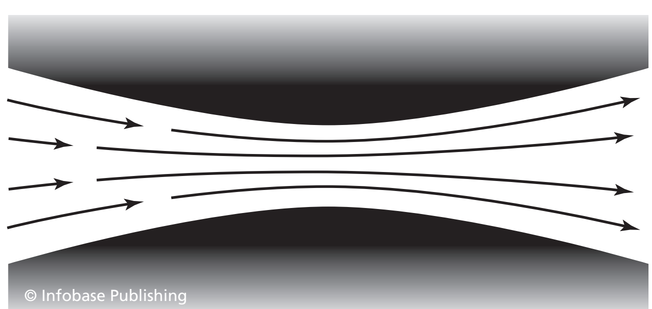
ventifact A ventifact is a desert pebble that has been worn away by the abrasive effect of wind-blown sand in such a way that it has clearly defined faces. The name is derived from two Latin words: *Ventus* means wind, and *facere* means make. Provided the pebble is not moved, the positions of the faces indicate the direction of the prevailing wind (*see* WIND SYSTEMS).

An einkanter is a ventifact that has only one edge. This indicates it was formed by the action of wind-blown sand arriving from predominantly one direction.

A dreikanter has three edges. The abrasive action of wind-blown sand is believed to loosen and remove mineral grains from the surface directly exposed to the wind until the pebble falls over, exposing a second side. This is abraded in turn until the pebble falls again, exposing a third side and finally producing a dreikanter.

Venturi effect When a flow of air is constricted, for example by tall buildings or hills, the wind accelerates. This is known as the Venturi effect, after the Italian physicist Giovanni Battista Venturi (1746–1822), who discovered it in 1791.

Air leaves the constricted area at the same rate as that at which it enters. In order to do so, the air must travel faster past the constriction. Constriction has the effect of bringing STREAMLINES closer together.



The constriction, which might be the walls of buildings or the sides of hills, draws streamlines closer together, accelerating the air through the constricted region.

The surface of Venus. This is a view of Cunitz crater. ***(NASA/Science Source)***

Venus atmosphere The planet Venus is of approximately similar size to Earth. Its mean diameter is 7,521 miles (12,104 km); that of Earth is 7,918 miles (12,742 km). It is closer than Earth to the Sun, orbiting at 0.72 astronomical units (AU); 1 astronomical unit is the average distance between the Earth and Sun. Venus orbits at an average distance of 66,932,000 miles (107,712,000 km) from the Sun, and Earth orbits at 92,961,000 miles (149,600,000 km). Gravity at the surface of Venus is 8.87 m/s^2, and at the surface of Earth it is 9.8 m/s^2.

Earth and Venus are very similar in these respects and are sometimes described as twin planets. The atmosphere and climate of Venus are very different from those of Earth, however.

The atmosphere of Venus consists of 96 percent CARBON DIOXIDE and 3.5 percent NITROGEN with traces of about 150 parts per million (ppm) of SULFUR DIOXIDE, 70 ppm of ARGON, 20 ppm of WATER VAPOR, 17 ppm of CARBON MONOXIDE, 12 ppm of HELIUM, and 7 ppm of NEON. The atmospheric pressure at the surface is 92 bars, compared with 1 bar on Earth.

The dense Venusian atmosphere, consisting almost entirely of carbon dioxide, produces a strong GREENHOUSE EFFECT, and combined with its closer proximity to the Sun this gives Venus an extremely hot, dry climate. The global average surface temperature is 867°F (737 K, 464°C). On Earth, lead melts at 621.5°F (327.5°C); the melting point would be higher under the greater atmospheric pressure on Venus, but probably lead would flow as a liquid on the surface of Venus, and this gives an indication of just how hot the climate is. It is hot enough to make rocks glow.

There is little variation in temperature between the equator and poles or between day and night, because of the strong and efficient transport of heat by the atmospheric circulation in both hemispheres. Surface winds blow at about 2 MPH (3 km/h) or less, but there are high-level winds blowing parallel to the equator at about 224 MPH (360 km/h). Such winds could not blow on Earth because they would be balanced by the CORIOLIS EFFECT (CorF). The magnitude of the CorF is proportional to the rotational speed of the planet, and Venus turns much more slowly than Earth, so one day on Venus is equal to 243 days on Earth. Consequently, the CorF is much weaker on Venus than it is on Earth. Venus also rotates in the opposite direction (the rotation is retrograde), so the Sun rises in the west and sets in the east.

Viewed from outside, the surface of Venus is entirely obscured by cloud. At one time the clouds were believed to be of WATER. Today they are known to consist of sulfuric acid droplets. Spacecraft have visited Venus on several occasions, and the surface has been comprehensively mapped, but the high pressure and temperature and strongly acidic atmosphere mean instruments on landers last for only a very short time on the surface.

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Viroqua Viroqua is a city in Wisconsin that was struck by one of the most severe tornadoes on record on the afternoon of June 28, 1865. On the basis of the damage it caused, the tornado has been judged F4 on the FUJITA TORNADO INTENSITY SCALE.

The tornado produced multiple vortices that sometimes merged into a single vortex, and it moved at an estimated 60 MPH (96 km/h) along a path that was 300 yards (275 m) wide and 30 miles (48 km) long. The tornado began to the southwest of Viroqua, passed through the southern part of the town, passed to the south of Rockton, and then dissipated. It lifted a schoolhouse from the ground, complete with the teacher and 24 students inside, then dropped it, killing the teacher and eight students. A total of 29 people were killed and at least 100 injured.

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virtual temperature The TEMPERATURE dry air would have if it were at the same DENSITY and pressure as moist air is called its virtual temperature. The virtual temperature of moist air is a little higher than its actual temperature.

By correcting for the effect due to the density of WATER VAPOR, the use of the virtual temperature makes it possible to apply the equation of state to moist air using a single gas constant (*see* GAS LAWS), rather than calculating constants separately for dry and moist air.

A PARCEL OF AIR that rises above the level of free convection (*see* STABILITY OF AIR) will reach a height at which its virtual temperature is equal to the temperature of the surrounding air. At this height the air will be neutrally buoyant and will rise no higher. It is said to have reached its equilibrium level, also known as the level of zero buoyancy.

viscosity Viscosity is the resistance a fluid presents to SHEAR forces, and therefore to flow. It is caused by the random intermingling of molecules at the boundary between two fluid bodies, one of which is moving in relation to the other. Such molecular mingling also transfers energy from one fluid body to the other. This transfer of energy is important in the transport of energy by liquids, but EDDY viscosity is by far the most important mechanism for energy transport in air.

The coefficient of viscosity is the force per unit area, applied at a tangent, that is needed to maintain a unit relative velocity between two parallel planes set a unit distance apart in a fluid. It is measured in newtons per square meter per second ($N/m^2/s$) in the SI system and dynes per square centimeter per second ($dyn/cm^2/s$) in the c.g.s. system.

The kinematic viscosity is the coefficient of viscosity of a fluid divided by its density. It is measured in square meters per second (m^2/s) in the SI system and square centimeters per second (cm^2/s) in the c.g.s. system (*see* UNITS OF MEASUREMENT).

visibility Visibility is the distance from which an observer is able to distinguish an object such as a tree or building with the naked eye. Expressed another way, it is the transparency of the air to visible light.

Visibility is measured at a WEATHER STATION with reference to a number of familiar objects at known distances from an observation point. It is necessary to make a number of measurements in different directions to determine the all-round visibility. The prevailing visibility is the greatest horizontal visibility that extends over at least one-half of the horizon around an observation point. It is the visibility that is reported on a STATION MODEL.

Surface visibility is the horizontal visibility measured by an observer on the ground, rather than in an airfield control tower. Unrestricted visibility is horizontal visibility that is not obstructed or obscured for at least 7 miles (11 km).

Variable visibility is the condition in which visibility increases and decreases rapidly while it is being measured. The visibility must then be given as the average of the measured values. Variable visibility is reported only if it is less than 3 miles (4.8 km).

An object is visible if the eye can detect a contrast between it and the sky. For most people this requires the object to be at least about 5 percent darker than the sky. The minimum detectable contrast is symbolized by E (the Greek letter epsilon).

Visibility is reduced by the presence of water droplets and solid particles in the air between the object and the observer and, to a very much smaller extent, by the air itself. Objects are visible because of light reflected from them to the observer. Between the object and the observer some of the reflected light is scattered (*see* SCATTERING) and some is absorbed, so only a proportion of the reflected light reaches the observer. This light mixes with airlight coming from other directions, which "dilutes" the light from the object, making it harder to see.

The loss of reflected light between the object and the observer is known as extinction, and the fraction of the light lost per unit of distance under given conditions is known as the extinction coefficient, abbreviated as b_{ext}. The extinction coefficient varies according to the size and DENSITY of droplets or particles.

If the extinction coefficient is known, the visual range (r_v) is given by:

$$r_v = \log_e \varepsilon / b_{ext}$$

Obscuration is the situation when the sky is completely hidden by a weather feature at ground level, such as FOG. Any atmospheric feature, other than clouds, that obscures a portion of the sky as seen from a weather station is known as an obscuring phenomenon. An atmospheric feature that reduces horizontal visibility at ground level, such as fog, SMOKE, or blowing SNOW is called an obstruction to vision. These terms are used in United States meteorological practice. Blowing spray is water that is blown from the surface of the sea to form spray in an amount large enough to reduce visibility significantly.

The precipitation ceiling is the vertical visibility that is measured looking upward into PRECIPITATION. This measure is used when precipitation obscures the CLOUD BASE. An indefinite ceiling is the condition in which the vertical visibility cannot be measured precisely, because it is determined not by the cloud base, but by fog, HAZE, blowing snow, sand, or DUST. Precipitation does not produce an indefinite ceiling.

volcanic eruptions When a VOLCANO erupts, the cloud of gas it ejects into the atmosphere may affect the climate. Part of the ejected material, called ejecta, often consists of WATER VAPOR and steam, as well as SULFUR DIOXIDE (SO_2) that is quickly oxidized to sulfate (SO_3) particles, which then react with moisture (H_2O) to form sulfuric acid (H_2SO_4). The ejecta cloud also contains rock that was vaporized by the high temperature in the magma chamber. The vaporized rock condenses as it mixes with the cold air, forming small particles of rock. This is the volcanic ash that falls to the ground, blanketing the surface.

Volcanic ash is quite unlike the ash from a wood or coal fire. It is highly abrasive, and when it mixes with water it forms a slurry that sets hard as it dries. Meteorologists track the movement of ash clouds and warn aircraft to keep well clear of them. Volcanic ash could wreck an aircraft engine. It is also highly dangerous if inhaled.

Ash that is ejected into the lower atmosphere remains airborne for a matter of hours or days before it settles or rain washes it to the surface. If the ash enters the stratosphere (*see* ATMOSPHERIC STRUCTURE), however, it may remain there for months. Stratospheric air movements then spread the plume, sometimes into a belt of material that encircles the Earth. Sulfate, sulfuric acid, and fine ash particles all reflect sunlight, thus increasing the planetary ALBEDO, and the cloud also absorbs solar radiation, which warms the stratosphere. Both effects combine to reduce the amount of solar radiation reaching the surface and lower temperatures in the lower atmosphere.

Not all eruptions eject sufficient material to affect the climate, and not all eruptions are violent enough to hurl material all the way into the stratosphere. From time to time, however, an eruption triggers a marked fall in surface temperatures. Some of the most important of these are listed here.

El Chichón is a volcano in Mexico that became active in 1982, after having remained dormant for several centuries. It began to erupt on March 26 and continued erupting until the middle of May. The final death toll from the eruption was estimated at about 2,000. There was an especially violent eruption on March 29 that killed 100 people living in nearby villages, and on April 4 a huge explosion released a cloud of dust and gas. The gas included up to 3.6 million tons (3.3 million tonnes) of sulfur dioxide, all of which was converted into sulfuric acid. By May 1, this cloud had encircled the Earth. In late June, the densest part of the cloud was detected at a height of 17.4 miles (28 km), and by the end of July the top of the cloud reached about 22 miles (36 km). A year later, the cloud had spread to cover almost the whole of the Northern Hemisphere and a large part of the Southern Hemisphere. It was the first cloud of volcanic material to be tracked by instruments on satellites, and it produced a marked warming of the lower stratosphere. In June, the cloud reduced the average global temperature by about 0.4°F (0.2°C).

Krakatau, formerly known as Krakatoa, is a volcanic island that lies in the Sunda Strait between Java and Sumatra, Indonesia. On May 20, 1883, the volcano became active, and on August 26 and 27 it erupted in a series of increasingly violent explosions. These were heard in Australia, 2,200 miles (3,540 km) to the southeast, and at Rodriguez Island, 3,000 miles (4,800 km) to the southwest. The eruption threw about 5 cubic miles (21 km^3) of solid particles to a height of more than 19 miles (30 km). Stratospheric winds distributed the DUST over most of the Earth, producing spectacular sunsets for the following three years, which was the time it took for the dust to settle. During those three years, the Montpelier Observatory, in France, recorded a 10 percent decrease in the intensity of solar radiation, and there was a small but significant fall in average temperatures.

Mount Agung (Gunung Agung) is a volcano on the island of Bali, Indonesia, that erupted violently in March 1963, ejecting large amounts of particulate material, together with sulfur dioxide and sulfate AEROSOL. Some of the sulfate entered the lower stratosphere, and the wind patterns at the time carried it into the Southern Hemisphere. Within a very short time aerosol droplets were detected between Bali and Australia. The absorption of solar energy by the stratospheric aerosols warmed the lower stratosphere by 11–12°F (6–7°C) and surface TEMPERATURES fell by about 1°F (0.5°C). After about six months, the aerosols had spread around the world, and they remained in the air for several years, producing spectacular sunsets, but no measurable climatic effect.

Mount Aso-San is a volcano on the Japanese island of Kyushu. The volcano is 5,223 feet (1,593 m) high and has one of the biggest calderas (craters) in the world, measuring 17 miles (27 km) from north to south and 10 miles (16 km) from east to west. Mount Asosan erupted violently in 1783, injecting a large amount of dust and aerosol into the stratosphere. The eruption was followed by unusually cold weather from 1784 to 1786.

Mount Katmai, a volcano in Alaska, erupted violently in 1912, ejecting an estimated 5 cubic miles (21 km^3) of dust high into the atmosphere. It was the most violent volcanic eruption of the 20th century. During the months that followed, observatories in California and Algeria recorded a 20 percent drop in solar radiation and the weather was unusually cool, although temperatures had been somewhat lower than normal before the eruption. A bishop's ring (*see* OPTICAL PHENOMENA) was seen following the eruption.

Mount Pinatubo is a volcano on the island of Luzon, Philippines, which erupted in 1991. It was the second most violent volcanic eruption of the 20th century (after Mount Katmai). The volcano had not erupted for 600 years. Activity began in April, and on June 14–16 the mountain split into pieces in a series of explosions. The eruption ejected dust and sulfate aerosol to a height of 25 miles (40 km). This spread over most of the world. The amount of material in the stratosphere reached a peak in September 1991, after which the amount began to decrease over the TROPICS. It did not peak until the spring of 1992 over latitudes 40–60°N and remained fairly constant until the end of 1992 over latitudes 40–60°S. It could still be detected over Hawaii and Cuba in January 1994. Absorption of solar radiation by material in the stratosphere caused a cooling of about 0.7–1.25°F (0.4–0.7°C) in the troposphere that lasted through 1992 and 1993.

Mount Spurr, a volcano in Alaska, erupted on June 27 and August 18, 1992, injecting dust and sulfur dioxide into the atmosphere. There is no record of any climatic effect.

Mount Tambora is a volcano in Indonesia (then the Dutch East Indies) that erupted in April 1815. The eruption was one of the most violent in the last few thousand years, and scientists calculated that it released at least 3.6 cubic miles (15 km^3) of dust and sulfuric acid aerosols that spread to form a veil over much of the Northern Hemisphere. The particles may have added to some that were still present from earlier volcanic eruptions at St. Vincent in the West Indies and Awu in Sulawesi. Temperatures fell by up to 2°F (1°C) in many areas, and wind patterns were distorted. The following year, 1816, came to be known as "the year with no summer." Snow, driven by a northeasterly wind, fell over a wide area of eastern North America in June 1816 and from June 6 to 11 the ground inland was covered in snow as far south as Pittsburgh. Connecticut had frosts at some time in every month of 1816, and there were some June days when the temperature did not rise above freezing in Québec City. Harvests failed in many parts of North America and Europe, but the altered wind patterns brought a fine summer to the north of Scotland, and there was a heat wave in Ukraine. The bad weather of 1816 may have been partly responsible for the worst outbreak of typhus Europe had ever experienced, lasting from 1816 until 1819.

volcanic explosivity index (VEI) The VEI is a classification of VOLCANIC ERUPTIONS that includes the estimated amount of material each category injects into the atmosphere. This is relevant to climate, because the more violent the explosion the more likely it is that some of the fine particles it throws into the air will penetrate the stratosphere (*see* ATMOSPHERIC STRUCTURE) where they may remain for months or even years. Particles in the stratosphere reflect incoming sunlight and may therefore have a climatic cooling effect experienced over a wide area.

The VEI also includes the frequency with which eruptions of each type occur, based on historical records. The full VEI is given in the table below.

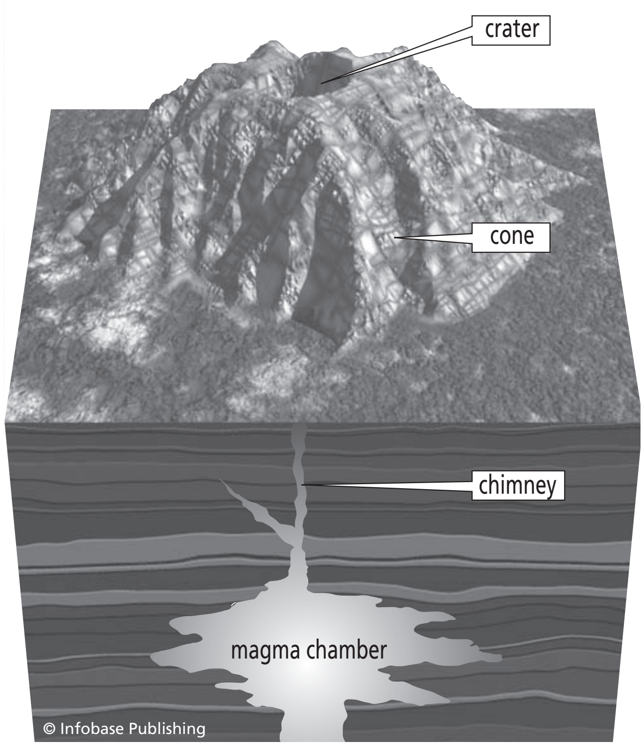
volcano VOLCANIC ERUPTIONS inject ash, DUST, rocks, and a variety of gases into the air. They play an important part in the cycles of elements by returning chemical elements to the atmosphere from below the Earth's crust.

Carbon, sulfur, and other elements that spend part of their time in the air eventually find their way into

Volcanic Explosivity Index

Index	Type	Plume height feet	Volume cu.feet	Eruption type	Frequency	Example
0	nonexplosive	<350	3,500+	Hawaiian	daily	Kilauea
1	gentle	350–3,500	35,000+	Hawaiian/Strombolian	daily	Stromboli
2	explosive	3,500–16,000	35 million+	Strombolian/Vulcanian	weekly	Galeras 1992
3	severe	10,000–50,000	35 million+	Vulcanian	yearly	Ruiz 1985
4	cataclysmic	33,000–82,000	350 million+	Vulcanian/Plinian	decades	Galunggung 1982
5	paroxysmal	>82,000	3.5 billion	Plinian	centuries	Saint Helens 1981
6	colossal	>82,000	35 billion+	Plinian/Ultra-Plinian	centuries	Krakatau 1883
7	supercolossal	>82,000	350 billion+	Ultra-Plinian	millennia	Tambora 1815
8	megacolossal	>82,000	3,500 billion+	Ultra-Plinian	tens of millennia	Yellowstone 2 Ma

(Ma means millions of years ago.)



A cross section through a typical volcano of the Strombolian type

the sea, and a proportion forms insoluble compounds that accumulate in the sediment on the seabed. Compression beneath the weight of overlying sediment and heat from the lower crust slowly turn this sediment into sedimentary rock. Seafloor spreading carries the layers of sedimentary rock lying on top of the rocks of the oceanic crust to a subduction zone, where one of the Earth's crustal plates is sinking beneath another (*see* PLATE TECTONICS). Subduction returns the sediment to the Earth's mantle, beneath the crust, and with it the elements that were once part of the air. Eventually, the mantle rock containing those elements may return to the surface in a volcanic eruption and the elements may be hurled high into the air.

A volcano begins as a space among the rocks of the crust into which mantle rock rises. Once it comes this close to the surface, the hot, semi-molten rock is called magma, and the space where it accumulates is a magma chamber. Magma continues to accumulate until its pressure forces it upward. Finding its way through weaknesses in the overlying rock, the rising magma makes one or more chimneys that eventually reach the surface. What happens then depends on the composition of the magma. This may seep over the ground surface, be thrown into the air, or it may explode violently. Magma that pours out at the surface is called lava.

There are different types of volcanic eruption. A Hawaiian eruption produces fountains of fire and very fluid lava that flows down the side of the volcano. Peléean eruptions, named after Pelé, the Hawaiian goddess of volcanoes, are violent and explosive. Plinian eruptions are also explosive and eject large amounts of material into the air. They are named after Pliny the Elder, who died in 79 C.E., when Vesuvius erupted in this way. Strombolian eruptions, named after the Italian volcano Stromboli, throw out thick lava that falls back to build a steep-sided cone. Surtseyan eruptions are named after the island of Surtsey, near Iceland, which was formed by an eruption of this type in 1963. Surtseyan eruptions are very violent. They happen when water pours into the vent leading to the magma chamber, causing a huge explosion. Vesuvian eruptions, named after Vesuvius, the volcano beside the Bay of Naples, Italy, are explosive, but occur after long periods of dormancy. Vulcanian eruptions happen when the pressure from trapped gases blows away the overlying crust of solidified lava. Vulcan was the Roman god of fire—and the Romans sensibly built their temples to him outside the city.

Voluntary Observing Ship (VOS) A VOS is a merchant ship that is equipped to act as a WEATHER STATION. Port meteorological officers (PMOs) recruit ships into the VOS scheme. PMOs also supervise the provision and installation of the necessary instruments.

The VOS scheme began in 1853, at a conference in Brussels that was convened by Matthew F. Maury (*see* APPENDIX I: BIOGRAPHICAL ENTRIES) and attended by representatives from 10 maritime countries. In 1984–85 there were about 7,700 VOS in the world as a whole. Numbers have declined since then (probably because of the decline in the size of the merchant fleets of several major industrial nations), and today the VOS fleet comprises more than 6,000 vessels from 49 countries. The United States has the largest number of VOS, with more than 1,600. The scheme operates under the auspices of the WORLD METEOROLOGICAL ORGANIZATION (WMO).

A port meteorological officer (PMO) is an official belonging to a national meteorological service who is appointed to supervise the Voluntary Observing Ships (VOS) scheme. PMOs are based at ports and spend much of their time visiting participating ships. They are responsible for enrolling vessels into the VOS scheme, supervising the supply, installation, and correct maintenance of the necessary instruments and other equipment, collecting the meteorological logbooks from ships returning to port, and generally ensuring that the weather reports from ships at sea meet the required standard.

Voluntary Observing Ships use SHIP code to send their reports. This is a version of the international synoptic code that is approved by the WMO for VOS use. Data contained in VOS weather reports are compressed into SHIP code before being transmitted by radio to a shore receiving station, from where they are passed to the WMO Global Telecommunications System.

A ship report is a weather report compiled on board a VOS at sea and transmitted to a shore receiving station. Regularly at midnight, 6 A.M., noon, and 6 P.M. UNIVERSAL TIME, officers on the VOS take observations of air TEMPERATURE, SEA-SURFACE TEMPERATURE, WIND SPEED, AIR PRESSURE, PAST WEATHER, and PRESENT WEATHER. They may also note the relative HUMIDITY, cloud cover, and state of the sea. The recorded data are compressed using SHIP code, stored in the onboard meteorological logbook, and transmitted to a receiving station on shore. The receiving station then passes the report on to the Global Telecommunications System of the World Meteorological Organization. When the ship reaches port, its meteorological logbook is handed over to the port meteorological officer. The contents of the logbook are used to augment the transmitted observations and help to build a long-term picture of the climate over the oceans.

Further Reading

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vortex A vortex is a spiraling movement in a fluid that affects only a local area. The fluid at the center of a vortex is usually stationary or slow-moving, but this calm center may be surrounded by gas or liquid that is moving very rapidly. In most vortices the fluid spirals inward toward a region of low pressure at the center. A circular vortex is a vortex in which the STREAMLINES are parallel to one another around a common axis.

A TORNADO is a vortex, and water flowing from a bathtub usually forms one. On a much larger scale, the polar vortex that forms each winter over Antarctica and in some winters over the Arctic encloses a large mass of very cold air. The tendency of a moving fluid to form a vortex is known as VORTICITY.

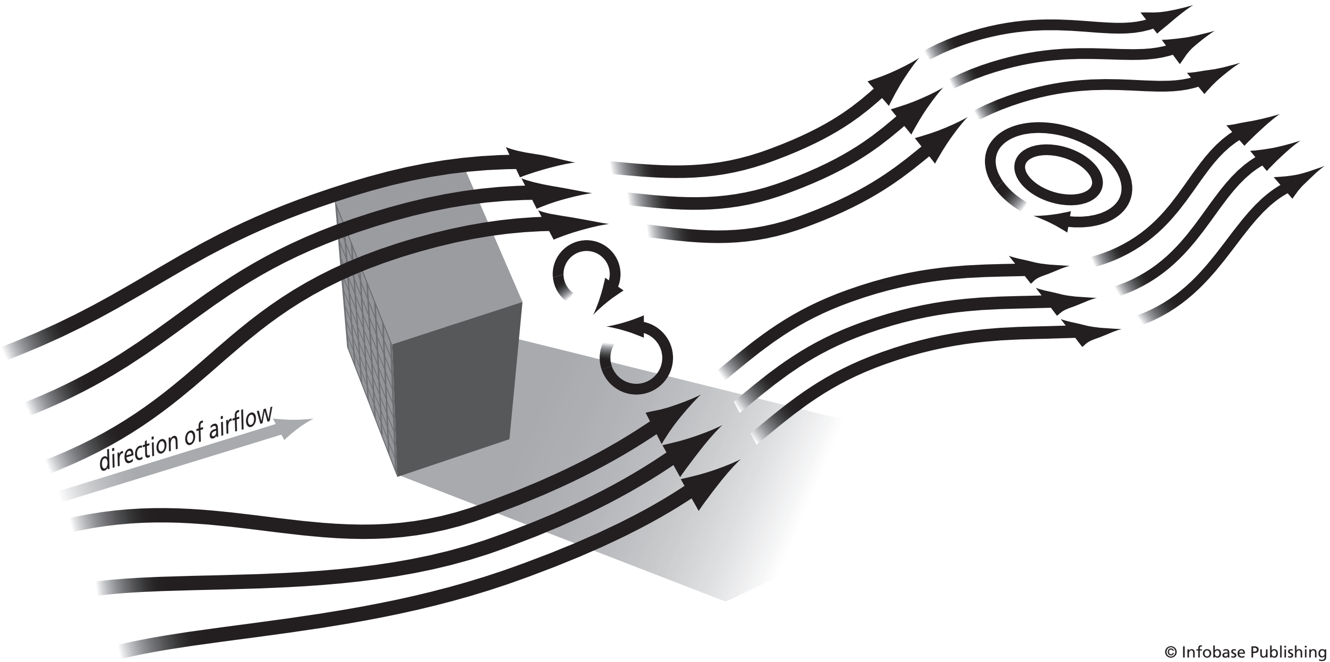
A bath plug vortex is a way of describing an atmospheric vortex by means of a familiar metaphor. Water leaving a bathtub usually forms a vortex that can be used to illustrate several features of atmospheric systems. Angular MOMENTUM is conserved. This can be seen by the acceleration of the water as it nears the center. The shape of the vortex resembles that of a tornado seen from above. The pressure surface is drawn down the center of the vortex, just as the tropopause (*see* ATMOSPHERIC STRUCTURE) is drawn down to the surface in the eye of a TROPICAL CYCLONE.

The polar vortex is the large-scale circulation that dominates the middle and upper troposphere in high latitudes and that is centered over the polar regions of both hemispheres. Air circulates cyclonically around the vortex. In the Northern Hemisphere, the vortex has two centers, one near Baffin Island and the other over northeastern Siberia.

A vortex also forms in winter in the stratosphere, with a strongly GEOSTROPIC WIND circulating around it. This is sometimes called the polar night vortex, and it is within this vortex that POLAR STRATOSPHERIC CLOUDS form. These are the sites of the chemical reactions by which OZONE is destroyed in the OZONE LAYER.

Vortices known as equatorial vortices develop at the center of equatorial waves over the Pacific Ocean. These travel westward toward the Philippines, but seldom intensify to become tropical cyclones.

A series of vortices that develops when a fast-moving flow of air passes an obstruction, such as a building, is known as a Karman vortex street. As the moving air approaches the obstruction, it divides into two streams. These pass to either side of the obstruction, and both of them accelerate due to the VENTURI EFFECT. If the air is moving gently and fairly steadily, the two streams decelerate and rejoin a short distance downstream from the obstruction. If the air is moving



A Karman vortex street is a series of vortices that develop downwind of an obstruction when the wind is strong.

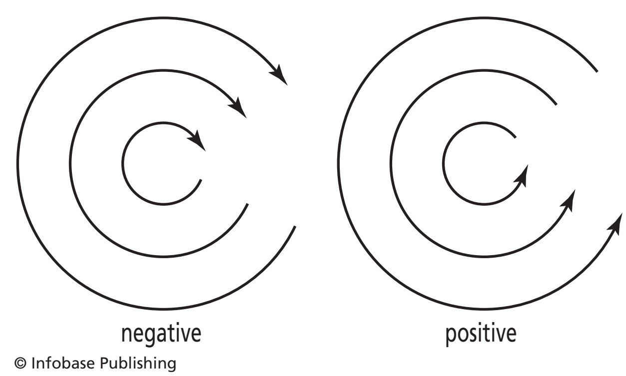
rapidly, however, the two streams remain separated, and a series of vortices develop between them. These rotate alternately clockwise and counterclockwise at a slower speed than the mean speed of the main airflow. The vortices are constantly forming and disappearing and they greatly increase the TURBULENT FLOW of air. The Hungarian-born American aerodynamicist Theodore von Kármán (1881–1963) was the first person to describe this phenomenon.

The word *distrail* is an abbreviation of dissipation trail. This is a line of clear air that appears in the thin cloud behind an aircraft. It is caused by vortices in the wake of the aircraft. These draw dry air down into the cloud, causing the cloud particles to evaporate. The distrail may form a straight line or a line of holes in the cloud. What appears to be a distrail is sometimes a shadow cast onto the cloud by a CONTRAIL above it.

vorticity Vorticity is the measure of the rate at which a moving mass of fluid turns about an axis. If a moving fluid is pictured as an immense number of minute solid particles, and if each of these particles is rotating as well as moving forward with the general flow, then vorticity is present in the moving fluid. The rotation of the imaginary particles will impart curvature to the general flow.

The concept of vorticity is of great importance in fluid mechanics, which describes the movement of fluids of all kinds and under all circumstances. In METEOROLOGY, vorticity affects the large-scale movement of air around CYCLONES and ANTICYCLONES.

Vorticity is a VECTOR QUANTITY as is VELOCITY, but its coordinates have three components, each compo-



Vorticity is the tendency of a moving fluid to rotate about an axis. Vorticity is conventionally described as negative if the direction of flow is clockwise and positive if the flow is counterclockwise. In the case of air or water movement across the surface of the Earth, the axis is vertical and the direction of motion is seen from above.

nent on a line at right angles to the other two. Two coordinates are sufficient to specify the position and movement of the body on a flat (two-dimensional) plane. If the body is also rotating, a third coordinate in the direction of the axis of rotation specifies the rotation. This third coordinate is the vorticity coordinate, or vorticity scalar.

Vorticity develops because the mass of fluid is moving in relation to the fluid adjacent to it. This generates SHEAR forces arising from the difference in velocities of the two fluids, so that the faster tends to curve around the slower.

Near the ground, friction causes moving air to turn about a horizontal axis that is at right angles to the wind direction. This generates EDDIES, but has no large-scale effect on weather. In the more important type of vorticity, air turns about an approximately vertical axis, so its movement is horizontal and the vorticity scalar is vertical.

Convergence and divergence (*see* STREAMLINES) generate vorticity in respect of a fixed frame of reference, in this case the surface of the Earth. The vorticity of air that turns about a local vertical axis is equal to twice the angular velocity. It is known as the relative vorticity, and in meteorology relative vorticity is always shown by the symbol ζ (the lower case Greek letter zeta).

Vorticity is also caused by the rotation of the Earth. This is necessarily so because the fixed reference frame of the Earth's surface is also rotating about a vertical axis with an angular velocity that is proportional to the angular velocity of the Earth and the latitude of the rotational axis of the mass of fluid. This aspect is known as the planetary vorticity, and its magnitude is always equal to that of the CORIOLIS EFFECT, known as the Coriolis parameter. Both are designated by the symbol f. The magnitude of f is zero at the equator and at its maximum at the North and South Poles.

By meteorological convention, vorticity in a counterclockwise direction is said to be positive, and vorticity in a clockwise direction is said to be negative. Seen from a position directly above the North Pole, the Earth rotates in a counterclockwise direction, and it rotates clockwise as seen from above the South Pole. Consequently, planetary vorticity is positive in the Northern Hemisphere and negative in the Southern Hemisphere.

The sum of the planetary vorticity and the relative vorticity ($\zeta + f$) is known as the absolute vorticity. Because of the conservation of angular MOMENTUM, the absolute vorticity remains constant ($d/dt\ (\zeta + f) = 0$). If minor components are omitted, such as those arising from the forces of BUOYANCY, FRICTION, and TORQUE, the value of absolute vorticity is given by the vorticity equation:

$$d/dt\ (\zeta + f) = -\ (\zeta + f)D$$

where d/dt is the rate of change and D is the rate of convergence (or divergence in the case of negative convergence, $-D$).

Because planetary vorticity is equal to the Coriolis parameter and absolute vorticity is constant, a change in the latitude of moving air causes a change in f that must be compensated by a change in ζ. If air in the Northern Hemisphere is diverted northward, for example, f increases, ζ decreases to compensate, and the vorticity becomes more negative, or anticyclonic. This turns the air in a southerly direction, decreasing f and increasing ζ, and vorticity then becomes more positive (cyclonic), turning the air northward again. This is how waves with a long wavelength develop in air that is flowing zonally (parallel to the equator). ROSSBY WAVES and LEE waves are examples of this effect.

Vostok, Lake Vostok Lake lies beneath the Russian VOSTOK STATION in Antarctica. The presence of WATER beneath the ICE SHEET was recognized in the 1970s, and the size of Lake Vostok was revealed by satellite RADAR altimetry in 1996.

The largest of about 70 subglacial lakes, Lake Vostok measures approximately 139 × 30 miles (224 × 48 km) in area and is about 1,588 feet (484 m) deep—about the same volume as Lake Ontario. Drilling of the Vostok ICE CORE was stopped about 330 feet (100 m) above the surface of the lake while ways were devised to sample its waters without contaminating them. It is possible the lake is populated by microorganisms and molecules of biological origin in an environment that has been isolated from the rest of the world for hundreds of thousands or even millions of years.

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Vostok Station Vostok is a Russian research station in Antarctica, located at 78.46°S 106.87°E, and at an elevation of 11,401 feet (3,475 m). Its name means "east," and it was opened on December 16, 1957.

Vostok is sited at the geomagnetic South Pole and at the center of the East Antarctic ICE SHEET. It is also at the southern COLD POLE. Scientists from many other countries work there. The primary project at Vostok has been the drilling of ICE CORES. Drilling commenced in 1980 and in 1985 reached a depth of 7,225 feet (2,202 m), beyond which it was impossible to continue with that core. A second core was started in 1984. In 1989, it became a joint Russian–French–U.S. project and in 1990 reached a final depth of 8,353 feet (2,546 m). A third core was started in 1990. It reached 8,202 feet (2,500 m) in 1992, and in 1998 it reached 11,887 feet (3,623 m). Ice from this depth is about 420,000 years old. In 2005, Chinese workers began planning to drill a core through Dome A, which is the highest point on the ice sheet, 13,124 feet (4,000 m) above sea level. Ice at the base of the dome is more than 900,000 years old.

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W

Walker circulation The Walker circulation is a movement of tropical air that was proposed in 1923 by Sir Gilbert Thomas Walker (1868–1958) and that has since been found to be correct. The Walker circulation is a slight but continuous latitudinal movement that is superimposed on the Hadley cells (*see* GENERAL CIRCULATION).

The movement occurs between the equator and about latitude 30° in both hemispheres as a series of cells, called Walker cells. Air rises over the tropical western Pacific Ocean and over the eastern Indian Ocean, both near Indonesia. CONDENSATION in the rising air produces towering clouds and heavy rain. At high level each of the rising air currents separates into two streams, one flowing eastward and the other westward. The high-level streams from neighboring cells converge and subside over the eastern Pacific, near the South American coast, and over the western Indian Ocean, near the coast of Africa. They diverge at low level (*see* STREAMLINES).

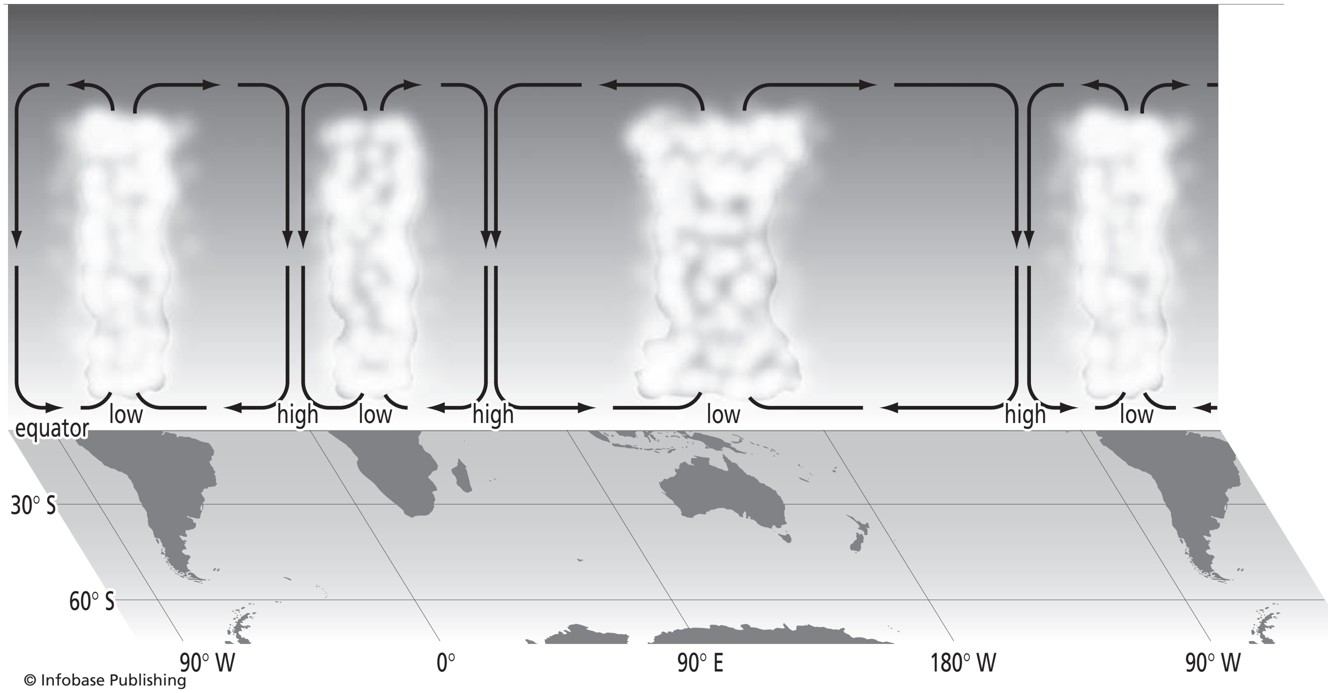
This circulation produces regions of low surface AIR PRESSURE over land in tropical South America, Africa, and Indonesia, where air is converging and rising. Areas of high pressure over the oceans, where air is subsiding and diverging at the surface, separate these low-pressure areas. This distribution of surface pressure produces a prevailing easterly flow (east-to-west) near the surface, which strengthens the easterly trade winds (*see* WIND SYSTEMS) of the Hadley cells.

The Walker circulation produces a very wet climate in Indonesia and a dry climate over western South America. Every few years the pattern changes, and the Walker circulation over the Pacific weakens or reverses. This change is known as the SOUTHERN OSCILLATION.

Sir Gilbert Walker was a British meteorologist and professor of meteorology at Imperial College, London. He had been appointed head of the Indian Meteorological Service, and in 1904 he was asked to look for a pattern in the occurrence of the Indian MONSOONS. A failure of the monsoon means that crops will wilt and the harvest will fail, and excessively heavy monsoon rains can destroy crops. In either case famine is the likely result. The monsoon had caused famines in 1877 and again in 1899, and the 1899 famine prompted the British authorities (who then ruled India) to see if the variations in monsoons could be predicted sufficiently far in advance to take steps to minimize the suffering they caused.

Walker approached the task by studying climate records from all over the world. In those days weather was believed to be a fairly local phenomenon, but Walker noticed that events in one place were sometimes accompanied by different events a long way away. When there was low surface pressure over Tahiti, pressure was often high over Darwin, Australia. When the Indian monsoon failed, the winter in Canada was mild. Relationships such as these, between events that occur great distances apart, are now known as TELECONNECTIONS, and Walker first discovered them.

From these studies Walker discovered a relationship between oscillations in the AIR PRESSURE over the eastern and western Pacific Ocean and the Indian monsoon



The Walker circulation is a pattern of latitudinal air movements over the Tropics that produce an easterly flow of air near the surface of the Pacific Ocean.

and rainfall in Africa. He called this periodic change in pressure distribution the Southern Oscillation, but he did not link it to the El Niño effect (*see* ENSO). It was not until 1960 that that connection was made, by Jacob Bjerknes (*see* APPENDIX I: BIOGRAPHICAL ENTRIES), who called this circulation the Walker circulation.

water Water, or dihydrogen oxide (H_2O) is able to exist in all three PHASES (gas, liquid, and solid) at temperatures that are common at the surface of the Earth. A pond in winter, when its surface is partly frozen, contains liquid water and solid ice, and the air immediately above the surface contains WATER VAPOR, which is an invisible gas. In this example, the gas, liquid, and solid are at different temperatures, but at 32.018°F (273.16K, 0.01°C) and at a pressure of 6.112 mb (0.089 lb/in^2, 0.18 inch of mercury) pure water exists in all three phases simultaneously. This is called the triple point of water (*see* BOILING).

Water is the only common substance that can exist in all three phases under the conditions found at the surface of the Earth. Ammonia (NH_3) is also a common substance, but at ordinary sea-level pressure (*see* UNITS OF MEASUREMENT) it freezes at -107.9°F (-77.7°C) and boils at -29.83°F (-34.35°C). Hydrogen chloride (HCl), also called hydrochloric acid, freezes at -173.6°F (-114.22°C), and boils at -121.27°F (-85.15°C). HCl is stored as a liquid in glass bottles by dissolving it in water, so the acid in the bottle in fact is a solution.

When water freezes, its molecules form an open pattern. This causes the water to expand as it freezes, and it also means that ice is less dense, and therefore weighs less, than liquid water and floats on top of it. This is another unusual property. Most substances are denser as solids than they are as liquids. If ice were denser than water, ponds, lakes, and the sea would freeze from the bottom up, rather than from the top down, and life would be impossible for many of the plants and animals that inhabit the bottom sediments.

Water with a molecular structure that differs from the structure of the main body of water of which it forms part is known as distorted water. This water forms a layer, several molecules thick, at the surface of a body of water and adjacent to the BOUNDARY LAYER.

Water also has a much larger HEAT CAPACITY than any other common substance. The very high heat capacity of the oceans means they absorb large amounts of heat with very little change in TEMPERATURE and then release their stored heat very slowly. This has a powerfully moderating effect on air temperatures. Without the heat capacity of the oceans, summer temperatures would be a great deal higher than they are and winter temperatures a great deal lower.

The water molecule is polar (*see* POLAR MOLECULE). This property makes it an excellent solvent, and the hydrogen bonds (*see* CHEMICAL BONDS) that link liquid water molecules also contribute to the capacity of water to form solutions from a wide variety of substances. This works in three ways. Some compounds, such as ethanol (C_2H_5OH), form hydrogen bonds with water molecules, allowing the ethanol and water molecules to mix freely with each other. Other polar compounds that are held together by covalent bonds become ionized (*see* ION) in water. Hydrochloric acid (HCl), for example, separates into H^+ and Cl^- ions. The H^+ then joins a water molecule, changing it into a hydronium ion (H_3O^+), and the Cl^- ions attach themselves to the H^+ ends of water molecules. Compounds linked by ionic bonds, such as common salt (NaCl), are pulled apart by the strong forces of attraction exerted by the positive and negative ends of water molecules. The Na^+ and Cl^- ions then attach themselves to water molecules and move with them.

Water is almost a universal solvent—a solvent in which anything will dissolve. Because of this it never occurs naturally in its pure form, but always as a solution. Its capacity as a solvent also means that living organisms can use it to transport nutrients and metabolic waste products in solution and that the chemical reactions by which organisms grow and maintain their tissues take place in solution. Without water, life on Earth would be impossible.

water balance **(moisture balance)** The water balance is the difference between the amount of water that reaches an area as PRECIPITATION and the amount that is lost by EVAPOTRANSPIRATION and RUNOFF. If the amount of precipitation is greater than the sum of evapotranspiration and runoff, there is water available for plant growth and to support animals and people. The water balance is therefore of great importance agriculturally, and it is also a strong influence on the type of natural vegetation an area will support.

Water balance is calculated for a specified area and for a specified time (usually one year) by:

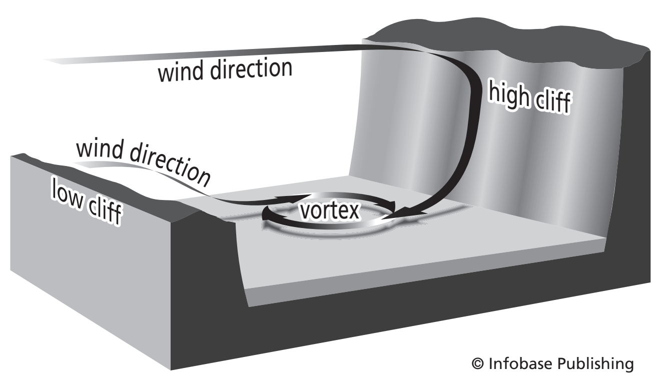
$$p = E + f + \Delta r$$

where p is precipitation, E is evapotranspiration, f is filtration, which is the amount of water absorbed and retained by the soil, and Δr is net runoff.

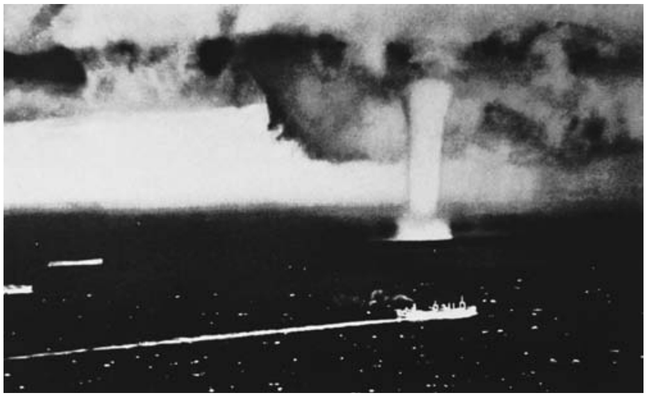
water devil A water devil is a phenomenon that resembles an aquatic DUST devil, but that is smaller, less violent, and of shorter duration. A water devil can result from vigorous CONVECTION over a water surface that is warmed unevenly. A column of air rises vigorously above a local hot spot, and surrounding air is drawn in at the base of the column. Convergence (*see* STREAMLINES) may then cause the air to rotate, forming a spiraling funnel of rising air. AIR PRESSURE is low at the center of the vortex. Air approaching it expands rapidly, cools adiabatically (*see* ADIABAT), and its WATER VAPOR condenses. This makes the funnel visible and, like a WATERSPOUT, it has a ring of spray around its base.

There is a second way a water devil can develop. Where a lake is bounded by low cliffs on one side and high cliffs on the opposite side, suitable wind conditions can produce EDDIES that generate a VORTEX over the water.

If the wind blows over the low cliffs, across the lake, and into the high cliffs, air striking the high cliffs will be deflected down the face of the high cliffs and back across the lake. When that happens, somewhere over the lake air moving away from the high cliffs will meet air moving toward the high cliffs. The resulting WIND SHEAR may set the air rotating. VORTICITY and



Wind blows over the low cliffs, blows across the lake, and rebounds from the face of the high cliffs, so two streams of air, moving in opposite directions, meet over the lake and produce a vortex.



A very large waterspout seen from an aircraft accompanying a North Atlantic convoy during World War II, from *Wenn die Elemente wüten* (When the elements rage) by Frank W. Lane *(Royal Air Force photograph, Historic NWS Collection)*

the conservation of angular MOMENTUM may then be sufficient to sustain a vortex, with air spiraling upward around it. Water devils of this type are freak occurrences. They last no more than a few minutes, and are seldom large, although they have been known to rise to a height of about 10 feet (3 m) and to have the strength to lift a small rowboat clear of the water and then drop it.

waterspout A waterspout is a TORNADO or column of spiraling air that occurs over water. It resembles a tornado and is larger than a WATER DEVIL. Some waterspouts are true tornadoes. They form in a cumulonimbus cloud (*see* CLOUD TYPES) that contains a MESOCYCLONE and may originate either over water or over land and then drift over water. A waterspout of this type is as powerful as any other tornado, and if it moves from water to land, it is just as dangerous.

Tornado funnels are usually dark in color because of the DUST and debris that is drawn into them and then spirals upward. Waterspouts are white, and if a tornado crosses from land to water, its color quickly changes because while it remains above the surface of the sea or a lake there is no dust and debris to darken it. The funnel consists entirely of air and water.

Around the base of a waterspout, air accelerating into the VORTEX whips up spray that forms a white cloud called a spray ring. Some of this water is carried up into the funnel, but most of the water in the funnel forms there, by the CONDENSATION of water vapor.

Air above the water surface is moist. As it is accelerated toward the center of the vortex, the moist air moves down a very steep PRESSURE GRADIENT to a region where the atmospheric pressure is much lower than it is outside the vortex. The change in pressure causes the incoming air to expand rapidly. As it expands, it also cools because of the conversion of heat to the KINETIC ENERGY required for expansion. Its TEMPERATURE falls below the dew point, and water vapor condenses. Condensation releases LATENT HEAT, adding to the instability of the rising air (*see* STABILITY OF AIR).

Waterspouts can also form in the absence of a mesocyclone. They are most likely to do so over shallow water when the weather is very hot, especially in sheltered places such as bays. Because most waterspouts occur close to the shore on fine afternoons in summer, they are often visible to people relaxing on the beach.

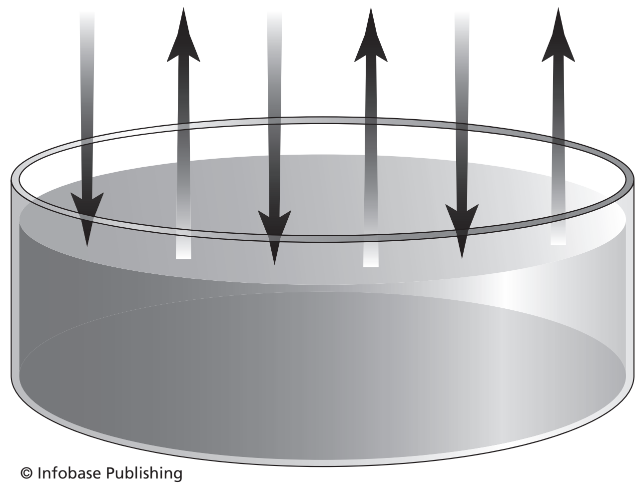
Near-shore waterspouts are caused by CONVECTION. Summer sunshine warms the water. Where the water is deep, it is only the surface layer that is warmed, and there is a limit to the temperature it can reach because the warm surface water mixes with the colder water beneath it. Over the open sea or a large lake, winds ripple the surface, increasing the mixing. Sheltered, shallow water, however, can be warmed all the way to the bottom, and its temperature can rise much higher.

Air is warmed by contact with the water surface and rises by convection, carrying a large amount of water vapor with it. As it rises, the air cools adiabatically (*see* ADIABAT) and its water vapor starts to condense, releasing latent heat that increases its instability. Cumulus congestus cloud (*see* CLOUD TYPES) starts to form. This does not extend to a height where the tem-

Waterspouts off the Bahamas Islands *(Joseph Golden/NOAA)*

perature is below freezing, and the cloud may produce no PRECIPITATION, but if the air is rising rapidly enough, the air being drawn in below the cloud may start to rotate about a vertical axis. The resulting vortex may then extend below the cloud as a spiraling column of air and water.

Waterspouts of this type are weaker than tornadoes. Most have a funnel about 150 feet (45 m) in diameter, although some can reach 300 feet (90 m), and they produce wind speeds of about 50 MPH (80 km/h). They occur along tropical coastlines, in the Gulf of Mexico, and in the Mediterranean, and are most frequent in the southern Florida Keys, where up to 100 form every month during the summer.



Water molecules are constantly escaping from an exposed water surface and being absorbed into it. This process is indicated by the broad arrows. Water molecules present in the air exert pressure on surfaces. This is the vapor pressure.

water vapor Water vapor is the gaseous PHASE of WATER (H_2O) in which the molecules of H_2O are no longer attached to one another by hydrogen bonds (*see* CHEMICAL BONDS) but can move freely and independently. Energy must be applied in order to break the hydrogen bonds and change liquid water into a gas. This energy is called the LATENT HEAT of vaporization and is 600 calories per gram (2,501 J/g) of liquid water at 32°F (0°C). A similar amount of latent heat is released when water vapor condenses into a liquid (*see* CONDENSATION).

When ice is exposed to very dry air, some of its molecules enter the air, turning directly from the solid to the gaseous phase without passing through a liquid phase. This change is called SUBLIMATION. The change in the opposite direction, from gas to solid, is called DEPOSITION. Sublimation requires the absorption of an amount of latent heat that is equal to the sum of the latent heat of melting and the latent heat of vaporization. At 32°F (0°C) this is 680 cal/g (2,835 J/g). Deposition releases exactly the same amount of latent heat.

Water vapor absorbs infrared radiation (*see* SOLAR SPECTRUM) at wavelengths (*see* WAVE CHARACTERISTICS) of 5.3–7.7 µm and beyond 20 µm. It is the principal greenhouse gas (*see* GREENHOUSE EFFECT) in terms of the amount of BLACKBODY radiation it absorbs. However, water vapor is not usually counted as a greenhouse gas because its atmospheric concentration is widely variable and impossible to control.

The partial pressure (*see* AIR PRESSURE) exerted on a surface by water vapor present in the air is known as the vapor pressure. Over an open surface of water or ice, water molecules are constantly escaping into the air by EVAPORATION or sublimation. These molecules add to those already present in the air, thus increasing the vapor pressure. Vapor pressure also drives water molecules to merge with the exposed surface. Consequently, there is a two-way motion of molecules leaving and entering the air. If the rates at which molecules are leaving and entering the air are equal, so there is no net gain or loss of water vapor, the water vapor is saturated, although it is usually the air that is said to be saturated.

wave characteristics A wave traveling through WATER (or AIR) possesses certain features that can be used to describe it.

Its wavelength is the horizontal distance between the crest or trough of one wave and the crest or trough of the next. The wavelength (λ) of a system of waves is related to their frequency (f) by $\lambda = c/f$, where c is the speed at which the waves advance (their celerity).

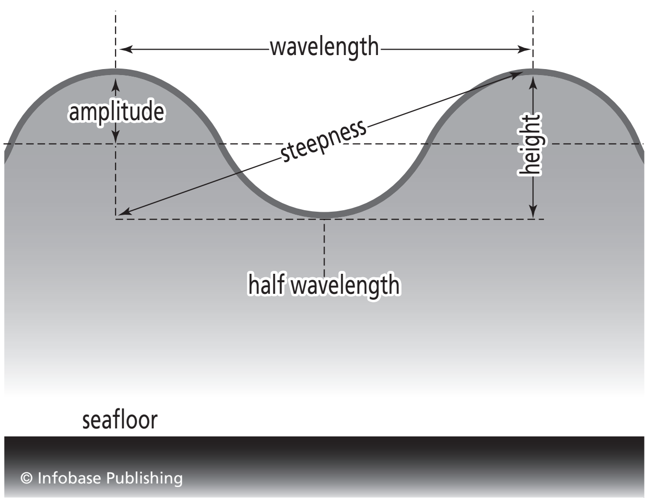
The wave amplitude is the vertical distance between the mean water level and the bottom of a wave trough or top of a wave crest. It is the distance by which the wave moves up and down. The amplitude is equal to half the wave height.

The height of the wave is the vertical distance between crests and troughs and is equal to twice the amplitude. Most sea waves are generated by the action of the wind, and the height of a wind wave is determined by the strength of the wind and the distance across which it blows (known as the fetch).

The steepness of the wave is given by the hypotenuse of a right-angled triangle, the other two sides of which are the wavelength and the wave height.

The number of crests (or troughs) that pass a fixed point in a unit of time is the wave frequency. Frequency is the rate at which any regularly repeating event recurs. In the case of waves, the frequency is the number of vibrations or oscillations that occur in a given time, usually one second. The frequency of a wave (f) is calculated by $f = c/\lambda$, where c is the speed at which the wave is moving and λ is the wavelength. The unit of frequency is the hertz (*see* UNITS OF MEASUREMENT).

Generally, the word *period* describes the amount of time that elapses between two events, and in particular the time that elapses between two repetitions of the same event. The wave period is the time that elapses between one crest or trough and the next passing a fixed point. The frequency of a wave is given by $1/T$, where T is the period, and the speed (c) of a wave is given by $c = \lambda T$, where λ is the wavelength. When air or water move within a confined space, such as a lake or coastal bay, the resulting waves may oscillate with a period that is determined by the configuration of the boundaries containing them. This is known as the natural period for that place, and it is equal to the reciprocal of the natural frequency.



Waves are described in terms of wavelength—the distance between one crest or trough and the next; height—the vertical distance between crests and troughs; amplitude—half the height; and steepness—the angle betwen the horizontal and a line drawn from a point level with a trough and directly beneath a crest to the top of the adjacent crest. Wave motion ceases at a depth beneath the troughs equal to half the wavelength.

The speed at which waves travel is known as their celerity. Celerity (c) is proportional to the wavelength (λ) and frequency (f) of the wave, such that $c = \lambda f$. This applies to waves in either air or water. In deep water, $c = (g\lambda/2\pi)^{1/2}$, where g is the acceleration due to gravity of 32.2 feet per second per second (9.81 m/s^2). Taking this into account, $c = 1.25\sqrt{\lambda}$. In shallow water, $c = (gd)^{1/2}$, where d is the depth of water, and therefore $c = 3.13\sqrt{d}$.

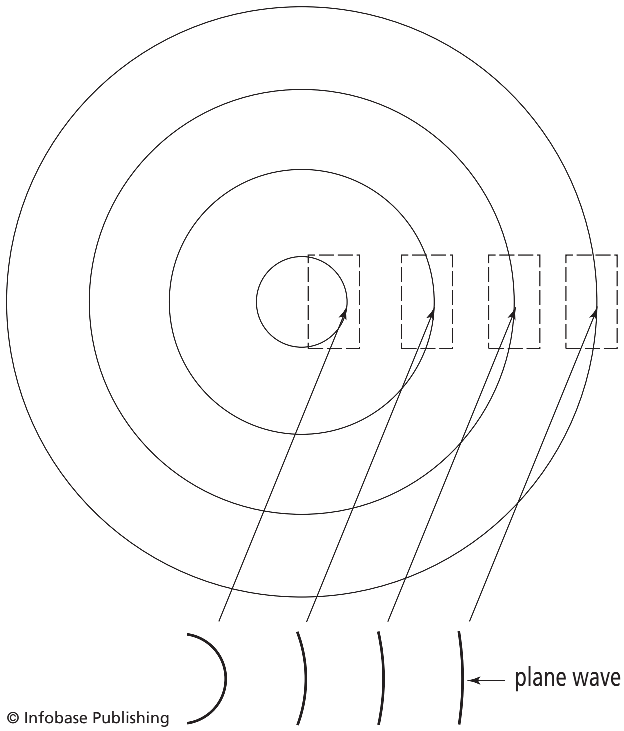
The wave equation is a partial differential equation that represents the velocity (v) and vertical displacement (ψ) produced by a wave as a function of space and time (t), where space is described by three coordinates x, y, and z. The equation can then be written as:

$$v^2\psi = \delta^2\psi/\delta x^2 + \delta^2\psi/\delta y^2 + \delta^2\psi/\delta z^2 = (1/v^2)\delta^2\ \psi/\delta t^2.$$

Waves travel in groups. Those with the longest wavelength are at the front of the group, and those with the shortest wavelength are at the rear. It follows (by $c = \lambda/T$) that the waves at the rear of the group are traveling fastest. They overtake the waves ahead of them, advancing through the group, but as they do so they lose height, and when they reach the front of the group, they disappear. The group advances as a whole at half the speed of the individual waves that compose it.

Waves travel through water or air, but they do not carry the water or air with them. A molecule of water or air, or a cork bobbing about on the water, describes a small circular motion. That is why a boat is rocked by waves, but not transported by them.

Molecules are affected by wave motion to a depth equal to half the wavelength, and at that depth the amount of molecular movement is negligible. Land slopes into the sea rather than meeting it abruptly. Consequently, as a sea wave approaches a coast, the sea becomes shallower. When the depth of water is less than half the length of the waves, the motion of particles near the bottom becomes flattened and the wave slows. This cannot alter the wave period, however, because waves continue to arrive at the same frequency. Instead, the wavelength decreases—the same number of wave crests pass in a given period of time, but the horizontal distance between them is reduced. The seafloor does not slope everywhere by the same amount, however, and the reduction in wavelength due to reduc-



A short arc taken from the outermost circle appears almost straight because of the length of the circumference. This is a plane wave.

ing water depth has the effect of aligning the waves with the submarine contours. It is why waves usually approach a shore at right angles.

Waves transmit energy imparted to them by the wind, tidal forces, or, in the case of TSUNAMIS, disturbances of the ocean floor. As they enter shallow water and slow, they continue to convey energy at the same rate. This causes the height of the waves to increase, and as their height increases so does their steepness. The circular motion of molecules at the crest is accelerated, and when it exceeds that of the wave itself, the wave becomes unstable. Its crest curls forward and spills. It is then a breaker.

Objects floating at the surface will move in the same way as the water molecules. In deep water they will move only vertically, but close inshore, where the waves are breaking and molecules at the wave crests are traveling faster than the waves themselves, they will be carried toward the shore. That is what makes surfing possible.

A capillary wave is a very small wave. It is the "puckering" on the surface of very still water that is produced by the slightest breeze. The capillary wave has a wavelength of less than 0.7 inch (1.7 cm) and the SURFACE TENSION of the water quickly restores the smooth surface.

An oscillatory wave is a wave that causes air or water to move about a point, but without advancing in the direction the wave is moving. Particles of air or water describe an approximately circular orbit, moving up and forward, then down and to the rear.

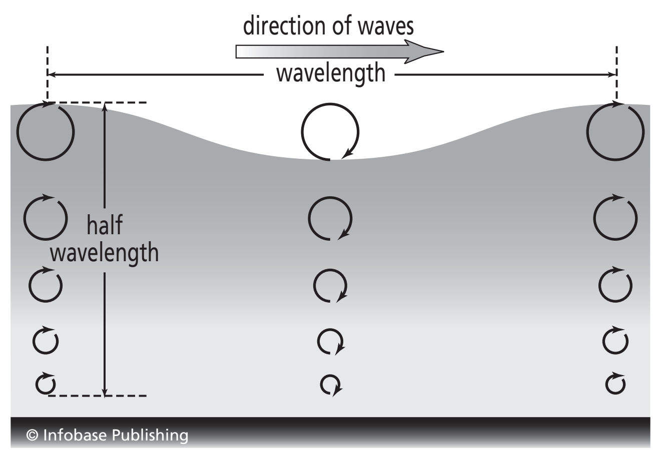
A plane wave is a wave front that is not curved owing to its distance from the source. As waves spread outward, like ripples on a pond, their circumferences increase in size until a point is reached at which any short section of the wave front is effectively straight. It is then a plane wave.

The wave front is the line joining all the points that are at the same phase along the path of an advancing wave.

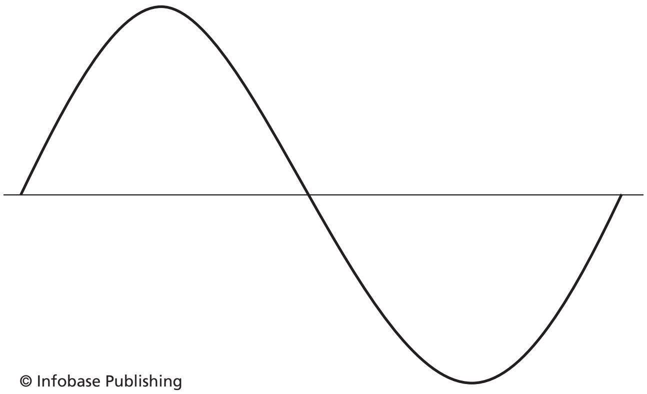
A wave or group of waves that moves in relation to the surface of the Earth is called a progressive wave. Waves that remain stationary in relation to the surface are called standing waves.

A traveling wave is a wave that moves through a medium, although the particles from which the medium is composed oscillate about a fixed point. A wave is a regular pattern of vertical or horizontal displacements. If the wave is traveling, it is the pattern of displacements that progresses, but not the particles that are displaced. Sound waves (*see* SPEED OF SOUND) and most ATMOSPHERIC WAVES are traveling waves.

A sine wave is a curve on a graph that corresponds to an equation in which one variable is proportional to



Waves cause the water to move in a circular motion. The waves move through the water, but the water itself does not advance.



A sine wave oscillates in a very regular manner.

the sine of the other. A point moving along the curve oscillates about a central point so that crests and troughs are of equal amplitude and wavelength.

weather Weather is the state of the atmosphere as it is in a particular place at a particular time or over a fairly brief period, with special emphasis on short-term changes. A description of the weather includes references to the current or expected TEMPERATURE, AIR PRESSURE, HUMIDITY, VISIBILITY, CLOUD AMOUNT and type (*see* CLOUD CLASSIFICATION), and PRECIPITATION. Weather is contrasted with CLIMATE, which is a much broader concept.

Any small-scale variation that occurs in the general state of the atmosphere at a particular time and place is called a disturbance.

A disturbance line is a weather system that occurs in spring and fall in West Africa. Moist air flowing from the southwest as part of the developing or fading MONSOON circulation is overrun by dry air from the Sahara. This produces a SQUALL line several hundred miles long that travels westward at about 30 MPH (50 km/h). The disturbance line produces squalls and THUNDERSTORMS, but dissipates once it has crossed the coast and encounters the cold water of the Atlantic. Disturbance lines are a major cause of rainfall in the periods immediately preceding and following the main monsoon season, between April and June and September and November.

weather balloon Surface WEATHER STATIONS gather data on conditions at ground level, and for many years meteorologists had no way of routinely monitoring the atmosphere anywhere higher than the roof of the tallest building in the area. Scientists used surface measurements and cloud observations to calculate pressures and winds at different altitudes. This allowed them to predict the track and speed of storm centers, but only approximately.

In 1893, Charles F. Marvin (1858–1943; *see* APPENDIX I: BIOGRAPHICAL ENTRIES), professor of METEOROLOGY at the UNITED STATES WEATHER BUREAU, invented the Marvin-Hargrave kite, together with its tethering mechanism and instrument package. The kite was a box kite, comprising a wooden frame covered with muslin. Typically there were 68 square feet (6.3 m^2) of fabric, although different weather conditions required different sizes of kite. Attached to the frame, the kite carried the Marvin Kite meteorograph, which was a set of instruments housed in an aluminum cylinder that moved pens linked to a chart on a rotating drum. The meteorograph weighed only 2 pounds (0.9 kg). The Marvin kite reel paid out the line of piano wire securing the kite. The reel could be operated manually or by a small gasoline engine, and as the kite rose the reel automatically registered the length of line it had paid out, the direction the line sloped, and the strength with which the kite was pulling on it. At intervals during its ascent, the kite paused for up to 10 minutes to allow its instruments to settle. The instruments recorded TEMPERATURE, AIR PRESSURE, HUMIDITY, and WIND SPEED.

Kites were deployed in 1898. Eventually there were 17 weather stations using them.

Kites were expensive, difficult to operate, and the scientists had to wait until the kite had been reeled in and they had removed the meteorograph before they had access to the data. By the late 1920s, they were being replaced by balloon sondes.

A balloon sonde is a package of instruments carried by a free-flying balloon that measure temperature, pressure, and humidity in the air through which they move. When the balloon bursts, the instruments fall to the ground by parachute. A balloon sounding is a measurement, or set of measurements, of atmospheric conditions. The word *sounding* is a nautical term, from the French verb *sonder,* which is derived from Latin *subundare, sub-* meaning under and *unda* meaning wave. To take a sounding originally meant to measure the depth of water.

Most sondes pass their data to a radio transmitter carried with them. A sonde from which data are transmitted by radio to a ground receiver is known as a radiosonde.

A radiosonde is a package of instruments, carried aloft beneath a balloon, that measure atmospheric conditions and transmits the resulting data by radio to a surface receiving station. The first weather balloon to be equipped with a radio transmitter flew in 1927. Modern radiosondes came into service about 10 years later. Each of the upper-air weather stations that form part of the network monitoring the upper air releases one radiosonde at midnight and one at noon UNIVERSAL TIME (Z) every day. By releasing all the balloons at the same time from stations all over the world, data from them can be compiled into a picture of conditions throughout the world at that time.

Midway between these launch times, at 6 A.M. and 6 P.M. Z, each station releases a balloon that carries only a RADAR reflector. This is tracked by radar to provide a profile of the wind speed and direction and the way this changes with height. A balloon of this type is called a wind sonde. A radiosonde that also carries a radar reflector, so it provides information on the wind at the same time as other meteorological data, is known as a rawinsonde. Wind direction is measured by noting the position of the sonde at intervals, usually of one minute. Because of the wind, the balloon does not rise vertically, but the data it records are taken to represent a vertical profile.

There are about 90 upper air stations in the United States, seven in Great Britain, and two in Ireland—approximately one upper air station for every 41,000 square miles (106,190 km^2) in the U.S. and one for every 13,000 square miles (33,670 km^2) in Great Britain and Ireland. In the world as a whole there are about 500 upper air stations.

The balloon is about 5 feet (1.5 m) in diameter when fully inflated, and it is filled with HELIUM. The instrument package is carried beneath the balloon at the end of a cable 98 feet (30 m) long. This length of cable prevents the contamination of instrument readings by effects from the balloon itself. Once released, the balloon rises at about 16 feet per second (5 m/s) to a height of 66,000–98,000 feet (20–30 km). As it climbs, air pressure around the balloon decreases. This allows the balloon to expand until it bursts. This happens about 1–1.5 hours after launch. The instrument package returns to the surface by means of a parachute. About one-quarter of the packages released are recovered and can be used again.

The instrument package consists of a main body that contains an aneroid pressure capsule (aneroid BAROMETER) for measuring atmospheric pressure, a battery to supply power, electronic devices that convert data into a form suitable for radio transmission, and the radio transmitter. Above the main body there is an open structure containing a skin HYGROMETER, and above that a plastic ring. The ring holds the fine wire of the electrical-resistance THERMOMETER. Humidity readings from the hygrometer are ignored at heights above 33,000 feet (10 km) because the instrument is unreliable at the very low temperatures prevailing at this altitude.

Radiosonde data are augmented by more than 2,000 reports every day from aircraft.

Much bigger balloons are used for upper-atmosphere research. These are also filled with helium, but they are only partly filled before launch. As they ascend, the helium expands to fully inflate the balloon. These research balloons are designed to return data from the middle and upper stratosphere (*see* ATMOSPHERIC STRUCTURE).

A balloon drag is a small balloon that is used to retard the first part of the ascent of a larger balloon in order to allow more time for making measurements. The drag balloon contains ballast to weight it and is inflated in such a way that it will burst at a predetermined height.

A pilot balloon, known as a pibal for short, is a weather balloon filled with a measured amount of HYDROGEN to ensure that it ascends at a predetermined rate. As it rises, the balloon is tracked using a theodolite. At intervals, the altitude of the balloon is calculated from its known rate of ascent, and its AZIMUTH angle is read from the theodolite. From this information the wind velocity is calculated for each height. If the sky is obscured by cloud, the height of the CLOUD BASE can be measured.

A theodolite is a surveying instrument that consists of a telescope with crosshairs in the eyepiece that is used for sighting and focusing on the balloon. The telescope is mounted on a tripod fitted with a spirit level to indicate when the instrument is horizontal, and it can be rotated in both the horizontal and vertical planes. The instrument is tilted until the telescope is focused accurately on the balloon. The horizontal and vertical angles between the instrument and the balloon are then read from graduated circles that are seen through a second eyepiece. These reveal the elevation and azimuth of the balloon. The method used to measure the speed and direction of high-level winds is called rabal.

A constant-level balloon is designed to rise to a predetermined altitude and then remain there. The balloon is contained within an inelastic cover, so its volume cannot exceed a certain value. This prevents the gas in the balloon from expanding until it becomes less dense than the air at the desired height. The altitude of the balloon cannot be controlled precisely, however, because it is affected by vertical air movements and by changes of temperature as it moves into and out of direct sunshine. These alter its volume and gas density.

Further Reading

Monmonier, Mark. *Air Apparent: How Meteorologists Learned to Map, Predict, and Dramatize the Weather.* Chicago: University of Chicago Press, 1999.

weather forecasting Meteorologists employed by their national meteorological and hydrological services work at central locations where they receive surface observations from WEATHER STATIONS and upper-air data from upper-air stations (*see* WEATHER BALLOON). They also receive data and images from orbiting WEATHER SATELLITES. It is their job to interpret all of this information and from it to predict how the weather will behave in the hours and days to come.

The scientists use a range of techniques in preparing their forecasts. Air mass analysis involves relating the characteristics of the AIR MASSES over a large area to the surface conditions illustrated on a synoptic chart (*see* WEATHER MAP). The surface chart is studied in conjunction with a number of other charts and graphs, including vertical cross sections of the troposphere (*see* ATMOSPHERIC STRUCTURE), charts showing the winds at different heights, constant-pressure charts, and Stüve charts (*see* THERMODYNAMIC DIAGRAM). The aim is to build up as complete a picture of the air masses as possible in order to improve the reliability of predictions of their future behavior.

The study of a SYNOPTIC chart of surface conditions is called surface analysis. A synoptic chart is one that is plotted from data contained in a synoptic report, which is any weather report that is based on synoptic WEATHER OBSERVATIONS, encoded using an authorized code, and transmitted to a weather center. Meteorologists abstract the information they need to identify air masses, frontal systems, and other features and to plot their locations.

A facsimile chart is a weather chart that is distributed as a fax from a central meteorological office. The device that transmits the chart is known as a facsimile recorder. In the United States, facsimile charts are sent daily from a center in Washington, D.C., to stations throughout the country.

A meteorogram is a diagram showing the way weather conditions have changed. Variable meteorological phenomena, such as TEMPERATURE, HUMIDITY, and AIR PRESSURE, are plotted against time.

A statistical forecast is one compiled from studies of past weather patterns. These are compared with present conditions and used to assess the statistical probability of the pattern repeating. This method can be used fairly reliably to predict a particular climatic feature, such as temperature or PRECIPITATION, over a short period. Very general forecasts over longer periods can also be compiled from a detailed knowledge of past patterns, using analog models.

A thermotropic model of the atmosphere is used in numerical forecasting. The model aims to forecast the height of one CONSTANT-PRESSURE SURFACE, usually that at 500 mb, and the height of one temperature, usually the mean temperature between 1000 mb and 500 mb. The THERMAL WIND is assumed to remain constant with height. Given these two parameters, it is possible to construct a forecast surface chart.

Numerical forecasting is one of the most important and widely used of modern techniques. Weather folklore is based on the belief that weather patterns repeat themselves reliably. If this is true, it means that a particular indicator, such as the color of the sky or shape of the clouds, can be depended on to be followed by weather of a particular kind. Folklore applies this crudely, but this element of modern weather forecasting is based on a similar idea. It assumes that weather in the future will closely resemble the kind of past weather that followed conditions similar to those obtaining at present. Unfortunately, the method is difficult to apply because the state of the atmosphere is rarely if ever identical on two occasions and, because the atmosphere behaves chaotically (*see* CHAOS), quite small variations quickly develop into major differences.

Numerical forecasting aims to replace empirical methods with one that is firmly based on known physical laws. The forecaster begins with detailed measurements of the state of the atmosphere at many different places at regular intervals. These reveal the way conditions are changing. These changes are interpreted mathematically, by applying certain equations to them. These include the EQUATIONS OF MOTION, the laws of thermodynamics (*see* THERMODYNAMICS, LAWS OF), the equation of mass conservation, the equation of state (*see* GAS LAWS), and equations of continuity. The equation of mass conservation relates changes in the DENSITY of air to the transport of its mass. The equations of continuity relate changes in the concentrations of the various constituents of the air, such as WATER VAPOR, CLOUD DROPLETS, and CARBON DIOXIDE, to their transport and to their sources and SINKS. Together these comprise the hydrodynamical equations. When used in conjunction with the temperature, pressure, humidity, and wind velocity at a particular time, they make it possible to predict the state of the atmosphere at a future time.

The difficulty of applying this method is obvious: It calls for a truly prodigious number of separate calculations. Vilhelm Bjerknes (1862–1951; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) saw the possibility of developing such a method as long ago as 1904. He was unable to proceed very far with it, however, because the detailed observations needed to supply the initial data were not available at the time. Lewis Fry Richardson (1881–1953; *see* APPENDIX I: BIOGRAPHICAL ENTRIES) made another attempt, which he published in 1922. This might have worked, but mathematicians have estimated that about 26,000 people would need to work full-time to perform by hand the calculations needed to predict the weather faster than it was occurring.

What Richardson needed was a computer, but it was not until 1953 that computers were sufficiently fast, powerful, and reliable to be used in weather forecasting. That was the year that the Joint Numerical Weather Prediction Unit (JNWP) was established in the United States. It began issuing forecasts in 1955.

Numerical methods are now used by most national weather services. Forecasters are supplied with prognostic charts that are generated by numerical models. Although these charts picture the way a weather system may develop, they do not in themselves constitute the forecast. Experienced meteorologists use them as tools to help them identify emerging patterns and to recognize the significance of what is happening. The forecast that is finally produced results from the combination of the numerical forecast and the interpretive skill of the meteorologist.

An important change in forecasting technique occurred in the early 1990s. Until that time the computational effort needed to produce a weather forecast was so great that from one set of input data forecasters were able to produce only one prediction. This was the weather they considered most likely, but the increase in computing power, and especially the availability of supercomputers for weather forecasting, allowed them greater flexibility. They began to use ensemble methods. To produce an ensemble forecast the scientist runs a numerical forecasting model repeatedly—typically between five and 100 times—with a slight change in either the initial condition or the numerical representation of the atmosphere for each run. This yields a number of forecasts, and the forecaster then evaluates the likelihood of each of them. Instead of a single forecast, the forecaster is able to predict the probability of a range of weather events. This is called a probability forecast.

A probability forecast states the expected likelihood of a particular type of weather, usually precipitation. The forecast might say there is a "60 percent chance of rain" or "a 0.6 chance of rain." Both mean the same thing, because probabilities can be expressed as a decimal between 0 (no chance at all) and 1 (absolute certainty). The statement means that during the forecast period there is a 60 percent chance that it will rain in a particular place and a 40 percent chance that it will not. It does not mean there is a 60 percent chance that rain will fall somewhere in the possibly large forecast area and a 40 percent chance that the entire area will remain dry. Precipitation is interpreted to mean 0.01 inch (0.25 mm) of rain or its equivalent at any particular place covered by the forecast at any time during the forecast period.

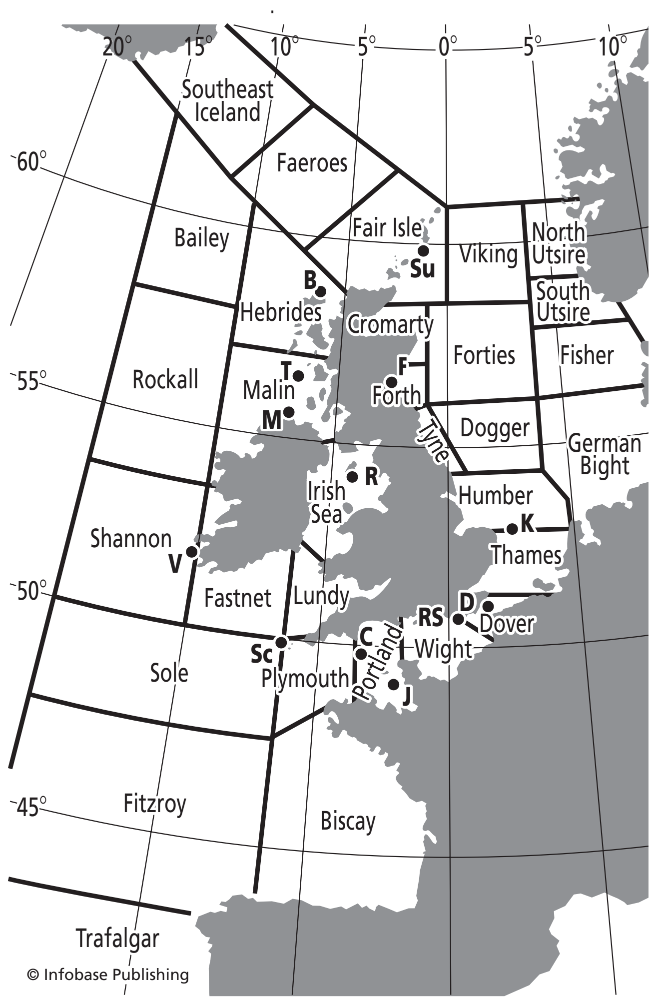
Prior to the introduction of ensemble methods, calculating the probability began by determining whether or not precipitation-bearing clouds will enter the area during the specified period. If it is fairly certain that they will (for example, because they are close to the edge of the area and advancing toward it), then there might be a 90 percent (0.9) probability of precipitation. The clouds may not pass over the entire area, however. Their size and predicted track might mean they will cross about 70 percent (0.7) of the area. The chance of precipitation in any particular place within the area is therefore 0.9 × 0.7 = 0.63, which is approximately 60 percent. This means there is a 60 percent chance that it will rain in any particular place, but there is a 90 percent chance that it will rain somewhere in the forecast area.

Forecasts must be tailored to the requirements of those who will use them. An area forecast is prepared for a specified geographic area. A local forecast covers a small area and is intended for the use of farmers, horticulturists, vacationers, and other people who need to know what conditions to expect in the next few hours or for up to about two days ahead. The local forecast is derived from the short-range forecast. The short-range forecast is compiled for a large area, and local conditions may be strongly affected by topography, distance from a coast, or the amount of exposed water surface in the area. The local forecaster modifies the general forecast in the light of these influences.

An aviation weather forecast is prepared for aircrews. It includes information relevant to the operation of aircraft, such as cloud base, cloud type, wind speed and direction at various heights throughout the troposphere, the risk of icing (*see* flying conditions), and clear air turbulence. A flight forecast is one prepared for a specific air journey. A route forecast is prepared for pilots. It provides them with details of weather conditions at various altitudes along the route they are planning to fly. Data from the route forecast are fed into a computer. This calculates the heading on which the aircraft should fly in order to follow the desired track over the ground or sea surface and the speed at which the aircraft will travel in relation to the surface (the ground speed) when it flies at its designated cruising airspeed.

A marine forecast is one prepared for the crews of ships at sea. Updated marine forecasts are broadcast at regular intervals. Forecasts issued by the British Meteorological Office, which cover the sea areas around the British Isles, including the Republic of Ireland, begin with a summary of conditions at 13 coastal weather stations, the positions of which are known to mariners. This is followed by a general summary of the way weather systems are expected to develop over the 24-hour forecast period. The summary states whether an area of high or low pressure will be centered in the area and, if so, the location of the center and the pressure at the center. More detailed forecasts, of pressure, change in pressure, wind direction and speed, precipitation, and visibility are then broadcast for each coastal sea area in turn. Forecasts for more distant sea areas, as far as the central Atlantic and north into the Arctic, are relayed to ships from weather satellites. In addition, warnings are issued of severe weather such as storms and gales.

Forecasts are issued for different lengths of time. The forecast period may range from less than 12 hours to several months or a season. Common sense would



The map shows the sea areas around the British Isles, which are used in marine forecasts. Weather forecasts for coastal shipping cover each of these areas individually. The letters show the location of coastal weather stations. Each forecast begins with reports from each of these stations in turn. They are: Tiree (T); Butt of Lewis (B); Sumburgh (Su); Fife Ness (F); Smith's Knoll Automatic (K); Dover (D); Royal Sovereign (RS); Jersey (J); Channel Light-Vessel Automatic (C); Scilly (Sc); Valentia (V); Ronaldsway (R); and Malin Head (M).

suggest that the shorter the forecast period the more accurate the forecast is likely to be, but this is not necessarily so, because more detail is usually expected in forecasts for very short periods than in those for longer periods. Individual SHOWERS and storms are short-lived and affect small areas, for example. Their likelihood can be reliably predicted over a particular area, but they cannot be predicted to strike a specific neighborhood more than one hour ahead. A forecast for a season, on the other hand, would be expected to state no more than whether it would be warmer, colder, wetter, or drier than usual over an entire region or even continent. Most forecasts cover the period up to 24 hours ahead and add a summary of the outlook for two or three days beyond that. These forecasts achieve a fair degree of accuracy in predicting the track and behavior of middle latitude weather systems and in anticipating large-scale events such as the approach of CYCLONES and ANTICYCLONES over the outlook period.

Nowcasting is the issuing of local weather forecasts for the immediate future, up to two hours ahead. These forecasts give warning of approaching severe STORMS and TORNADOES.

A daily forecast is one issued for the period from 12 to 48 hours ahead.

A short-range forecast covers a period of up to two days. The forecast is based partly on synoptic methods, but nowadays more often on numerical forecasting. The synoptic method aims to predict future patterns of high-level pressure distribution and the THICKNESS of the layer between 1,000 mb and 500 mb, and then to judge the surface conditions that are likely to result. Short-range forecasts are generally fairly accurate, but they are limited. Weather systems may change the speed at which they move, and when the air is moist and unstable (*see* STABILITY OF AIR), it is impossible to predict where and when showers will occur. Consequently, these are forecast somewhat vaguely, as "scattered showers" or "showers with bright periods."

A medium-range forecast covers a period of 5–7 days. It is compiled in the same way as a short-range forecast.

A long-range forecast covers a period up to two weeks ahead and sometimes up to one month ahead. Forecasters compiling a long-range forecast cannot use the methods appropriate to short-range forecasts, because these describe atmospheric conditions with a lifetime of no more than about seven days. Instead,

Lighthouse in a storm. Reliable weather forecasts save lives at sea. ***(Mariners Weather Log/Historic NWS Collection)***

forecasters rely on statistical methods in which current tendencies, such as BLOCKING, are projected into the future. This requires making allowance for the behavior of the JET STREAM and the stage that has been reached in the index cycle (*see* ZONAL INDEX). The influences of surface features, such as lying SNOW, are taken into account, and in coastal areas so is the SEA-SURFACE TEMPERATURE. Analog CLIMATE MODELS provide an alternative approach. Although large amounts of data are available to forecasters and they have access to powerful models, long-range forecasts are inherently unreliable. This is because weather systems behave in a chaotic fashion (*see* CHAOS), so variations in the initial conditions that are too small to detect can produce widely divergent outcomes.

The initial condition is one of the values that are used as the base from which later values are calculated. For example, a weather forecast represents a set of calculations that aim to predict the way the weather will change from one state to another. The change is calculated from a set of measured or estimated values for a range of factors including temperature, pressure, humidity, and wind at various heights. These values are the initial conditions. Very small errors in the initial conditions tend to become increasingly exaggerated as the weather develops and the calculated values diverge from them. Because such discrepancies are too small to be noticed, the reliability of a forecast decreases with time. The acute sensitivity of a developing system to its initial conditions makes the development chaotic.

Forecasters use a variety of mathematical models of the atmosphere to assist them. A BAROTROPIC model is one used in numerical forecasting. At each level this model assumes the atmosphere to be barotropic. In a barotropic atmosphere the winds are GEOSTROPHIC, and there is no convergence or divergence (*see* STREAMLINES). In an equivalent-barotropic model it is assumed that air movements are not affected by FRICTION and are adiabatic (*see* ADIABAT) (that is, warmed and cooled as a consequence of the vertical movement of the air), and the vertical WIND SHEAR of the horizontal wind is proportion to the horizontal wind itself. The atmosphere is hydrostatic equilibrium (*see* HYDROSTATIC EQUATION) and quasi-geostrophic balance, which means air movement is controlled primarily by the PRESSURE-GRADIENT FORCE and the CORIOLIS EFFECT. In this atmosphere the wind direction does not change with height, all the contours on any CONSTANT-PRESSURE SURFACE are parallel, and vertical movements are presumed to be equivalent to those at an intermediate level, known as the equivalent-barotropic level.

Envelope orography is a technique that is sometimes used in the mathematical models used in weather forecasting. It assumes the valleys and passes in mountain ranges are filled mainly with stagnant air. This allows them to be ignored, effectively increasing the average height of the mountains. The disadvantage of this simplification is that increasing the average height of the mountains also increases the extent to which they block the passage of air to a value that exceeds the real value.

The accuracy of a forecast is known as its skill, and this must be checked. A skill score can be calculated by comparing the forecast with a reference standard. This standard may be a description of the weather situation prevailing when the forecast was compiled, and therefore assuming no change in the weather, or a forecast made by selecting one feature at random. Many forecast methods are tested against a type of random forecast in which it is assumed that the weather will not change at all.

Applying any technique to measure the accuracy of a weather forecast is called forecast verification. Verification is based on comparisons that are made between the conditions that were predicted and those which actually occurred. The accuracy of the forecast is then given a numerical score. Forecast skill is measured on a scale that ranges from 0 (completely wrong) to 1 (completely correct). The skill measures the predictive power of the forecast or of a forecasting method. For example, a forecast that it will not rain tomorrow in Death Valley is very likely to be correct, but making it demands little of the forecaster beyond a knowledge of the climate in Death Valley. Consequently, the forecast has very little predictive power. Forecast skill is usually measured by comparing the accuracy of a forecast with that of a climatological forecast or a persistence forecast.

A climatological forecast for a region is one that is based on its CLIMATE, rather than on a projection of the current synoptic situation, but with allowance made for such important features as FRONTS, pressure systems, and the location and strength of the jet stream.

A persistence forecast predicts a continuation of present conditions for several hours ahead. Such a forecast might state that the rain that is falling now will continue to do so, or that the present fine weather will remain unchanged. Such a forecast cannot predict changes in the direction or speed with which weather systems move or the formation or dissipation of frontal systems. Consequently, a persistence forecast usually remains valid for no more than 12 hours, seldom for as long as a full day, and it often fails in as little as six hours.

A forecast-reversal test is used to measure the usefulness of a method for forecast verification. The same verification method is applied simultaneously to two weather forecasts. One is an actual forecast, and the other is a fabricated forecast that predicts the opposite conditions. If the real forecast predicts rain, for example, the fabricated forecast predicts dry weather, and if the real forecast predicts wind, the fabricated one predicts calm. Each forecast is given an accuracy score on the basis of the test, and the two scores are compared. The comparison amounts to an evaluation of the verification test, because the real forecast should achieve a markedly higher score for accuracy than the fabricated one.

weathering Weathering is the general name for all of the processes by which solid rock is broken into ever smaller fragments and finally into particles ranging in size from those of clay, which are less than 0.00004 inch (4 μm) across, to sand grains up to 0.08 inch (2 mm) across. Not all weathering is due to the physical processes associated with weather. Chemical solutions that originate deep below the surface and rise through fissures in crustal rocks react with particular minerals in the rock. This makes some minerals soluble, so they are removed in solution. PRECIPITATION delivers WATER to the surface. Precipitation is naturally acid, because of the CARBON DIOXIDE and other gases that have dissolved in it. As the water filters downward through the soil, it dissolves some minerals, leaving rocks pitted. If air enters the cracks, other minerals will be oxidized. These changes, known as chemical weathering, weaken and fragment rock. They also tend to smooth it, because sharp corners and protrusions present large surface areas on which the chemical reactions can take place, so they are attacked more rapidly than flat rock faces.

Rock at the surface is directly exposed to physical weathering processes. In middle and high latitudes, water seeps across rock surfaces to places where water is freezing, forming ice lenses, and the freezing process alters the crystal structure of minerals, detaching fragments. In spring, the ice melts and the rock fragments are washed from the rock by the melting water or blown away by the wind. In warmer, drier climates, the rain reacts with minerals to form chemical salts that crystallize when the rain ceases and the rock dries, expanding as they do so. Crystallization, especially of common salt (sodium chloride, NaCl), causes rocks to crack. A violent STORM may cause rocks that have been weathered from below to fall down hillsides. As they fall, the rocks accelerate and detach other rocks, to produce a rockfall.

Weathered rock is subject to EROSION. On sloping ground, rocks and rock particles that have been broken from the main rock mass may suddenly slide downhill. Landslides occur when heavy rain turns soil to mud, which lubricates the ground beneath the rocks. Heavy rain can also shift large masses of soil, which descend as mudslides.

Rockfalls, landslides, and mudslides are known collectively as mass wasting. If they occur in populated areas, they can cause appalling devastation.

weather lore People have always tried to predict the weather. They have needed to know when to sow and harvest their crops, when to shelter their animals from an impending storm, and when it was safe to set sail on fishing expeditions or sea journeys. Until the invention of TELEGRAPHY there was no way weather observations made at points scattered over a large area could be brought to a central point quickly enough to produce a SYNOPTIC picture of weather conditions that might make accurate forecasting feasible. Instead, people had to rely on experience and local knowledge to interpret the signs they could see around them. These signs and their meanings became incorporated in sayings and short verses that made them easier to remember.

Predictions were also associated with gods and in Christian cultures with saints. This link derives from the time when the weather was believed to result from the direct intervention of supernatural beings. STORMS, HAIL, gales, and warm sunshine were all produced at the whim of these beings. Many of these old associations survive.

Lore, used in this sense (the word has other meanings), is a body of tradition or knowledge on a particular subject. Weather lore is the accumulated traditions and observations with which our ancestors attempted to interpret weather signs and forecast the weather. Possibly it was the Greek philosopher Theophrastus (371 or 370–288 or 287 B.C.E.) who compiled the earliest written collection of sayings about the weather. Theophrastus was a student of Aristotle (384–322 B.C.E.; *see* APPENDIX I: BIOGRAPHICAL ENTRIES). Evidently he talked well, because it was Aristotle who gave him the nickname Theophrastus, which means "divine speech." His real name was Tyrtamus, and after Aristotle retired he took over the Lyceum (school) Aristotle had founded. Theophrastus is best known as the founder of the science of botany, but he also wrote *On Weather Signs* and *On Winds,* two short books that describe natural signs indicating rain, wind, storms, and fair weather. The Greek poet Aratus (*ca.* 315–*ca.* 245 B.C.E.) also collected some weather sayings. About half of his only surviving complete work, *Phaenomena,* is devoted to them. The collections made by Theophrastus and Aratus were passed down from generation to generation, translated into Latin and repeated by Roman authors such as Virgil (70–19 B.C.E.), and were absorbed into many European cultures.

Religious festivals, mostly held to celebrate particular saints, mark the progress of the Christian year, and the weather on those days is often believed to set the pattern for the period that follows. Days that are traditionally held to be significant in this way are called CONTROL DAYS, and they include Candlemas, Easter Day, and

Christmas Day. The saints whose days predict the weather to come include Saints Bartholomew, Hilary, Luke, Martin, Mary, Michael and Gallus, Paul, Simon and Jude, Swithin, and Vitus. The dog days (*see* WEATHER TERMS) are inherited from Roman belief, and Groundhog Day is also a day when the weather is foretold.

Other beliefs are based on direct observation. Red sky in the evening indicates a fine day tomorrow, for example; dew in the night, rain before seven, and a gray mist at dawn also mean a fine day to come.

The appearance and behavior of familiar plants and animals is also held to foretell the weather. Cows lie down when rain approaches, but that is only one of the ways they can be used as forecasters.

Some of the traditional beliefs are accurate, but most are not. This may be because the original ideas behind them have become corrupted over the generations. There is not the slightest doubt that people whose lives sometimes depend on the weather, such as sailors and shepherds, are able to read signs of approaching wind, storms, and fine weather.

Many familiar animals are supposed to predict the weather through changes in their behavior. Cows can predict a range of conditions in addition to the supposed link between rain and whether the animals are standing or lying. If a cow tries to scratch its ear, there will soon be a SHOWER. If it beats its flanks with its tail, there will be a THUNDERSTORM. If the cows gather at the top of a hill, the weather will be fine, but if they move to lower ground it will be wet or stormy. If they stampede with their tails held high, there will be rain and thunder. In cold weather, cows will lie down at the approach of rain or huddle together in a sheltered place with their tails to the wind.

Some of these observations may be reliable, in particular the stampeding reaction to an approaching storm. Cows behave like this because parasitic flies that lay their eggs on the skin of cows are at their most active when the air is warm and humid—the conditions that precede a storm. They make a high-pitched buzzing sound as they fly, and this sound will make cows raise their tails and run.

If a goat grazes with its head facing into the wind, the weather will be fine. If it grazes with its tail to the wind, the weather will be wet.

An old English country belief holds that pigs can see the wind. When gales are imminent, they become very restless, running around their sties and scattering their bedding.

Barn swallows (*Hirundo rustica*) are migratory birds that spend the winter in low latitudes and migrate northward for the summer. Their appearance shows that summer has arrived, but the swallows do not arrive all together. It can happen that a few arrive first, probably carried by a favorable wind the others missed. Hence the saying "One swallow does not make a summer."

Even the barnyard rooster can predict the weather, though it is difficult to see how this saying works:

If the cock goes crowing to bed,
He'll certainly rise with a watery head.

There are plants that are believed to predict the weather. Scarlet pimpernel (*Anagallis arvensis*) is also known as poor man's weather-glass and shepherd's weather-glass. It is a small, herbaceous plant that grows on sand dunes and open grassland throughout most of Europe. It is quite common. Its tiny scarlet flowers, which appear from June through August, are reputed in weather lore to predict rain reliably. When the weather is to be sunny, the flowers open, and they close when rain threatens.

Months of the year are associated with particular types of weather, and sometimes months have descriptive nicknames. January is still winter and fine, mild days are deceptive. "A January spring is worth nothing" is one country saying. Another warns that "March in January, January in March."

"February fill dyke, black or white" is an English country expression that refers to the fact that in Britain February is usually a cold, wet month. In parts of England a dyke is a ditch (in Scotland and other parts of England it is a stone wall), and the saying means that in February the ditches will be full either of water (black) or of snow (white).

February 2 is Groundhog Day, the day on which an old tradition holds that the spring weather can be predicted. In parts of North America, this is the day on which the groundhog is said to emerge from hibernation to look for his shadow. If he sees it, he anticipates bad weather and returns to his hole for a further six weeks. If he cannot see his shadow, because the day is cloudy, he takes this as a good omen and remains above ground, anticipating fine weather.

February 2 is also Candlemas Day (so-named because it used to be celebrated by candlelight), and there is an ancient rhyme from which the Groundhog Day tradition may be derived:

If Candlemas be fair and bright,
Winter'll have another flight.
But if Candlemas Day be clouds and rain,
Winter is gone and will not come again.

March many weathers is an English expression that encapsulates the variability of the weather as winter is giving way to spring. This is one of several folk sayings about March weather. The saying "If March comes in like a lion it goes out like a lamb; if it comes in like a lamb it goes out like a lion" refers to windiness. Mists cannot form in strong winds. This is reflected in "As many mists in March as there are frosts in May." "March windy, April rainy, clear and fair May will be" is an English saying that also occurs in French and German.

The spring (in the Northern Hemisphere) EQUINOX occurs in March and gives rise to a folk belief in both the United States and Britain that gales are more common at the equinoxes. These are called equinoctial gales, but there is no basis for the belief.

May blossom is a country name for the flowers of the hawthorn (*Crataegus monogyna*), a common hedgerow shrub or small tree that flowers in the month of May. In temperate regions, May is a transitional month between spring and summer and consequently it can bring wide variations in temperature. In Britain, May frosts are fairly common, but so are pleasantly warm days. This variability gives rise to the old country saying: "Ne'er cast a clout till may is out." A clout (cloth) is any warm winter garment, but opinions differ as to whether "may" refers to the month or to may blossom.

Mild days that occur during autumn and early winter are sometimes associated with saints' days that fall around the same time. According to a British folk belief, a period of mild weather often occurs around St. Luke's Day (October 18) and ends at Saint Simon and Saint Jude (*see* CONTROL DAYS). Another period of mild weather occurs around St. Martin's Day (November 11).

Other predictions are based on observations of meteorological phenomena. Dew in the night is a piece of weather folklore that predicts a fine day in summer.

Dew in the night,
Next day will be bright.

This is often true.

According to weather folklore, gray mist at dawn is a sign that the summer day to follow will be fine.

Gray mists at dawn,
The day will be warm.

It is often true that:

Rain before seven,
Fine before eleven.

This folk saying is fairly reliable, because bad weather that occurs very early in the morning has ample time to clear.

Probably the most famous example of weather lore is the observation that a red sky often indicates the weather that is likely to occur in the next few hours.

Red sky at night, shepherd's delight;
Red sky in the morning, shepherd's warning.

The saying is not entirely reliable, because its accuracy depends on the rate at which weather systems are traveling, but it is correct more often than not. There are several versions of the rhyme (one substitutes "sailor" for "shepherd"), and the weather lore of many European cultures makes the link between a red sky and the approaching weather.

When the Sun is low in the sky, at dawn and sunset, its radiation travels obliquely through the atmosphere, and so its path through the air is much longer than it is when the Sun is high in the sky. Blue and green light are scattered repeatedly by collision with air molecules (*see* SCATTERING), allowing orange and red light to pass. If the air contains DUST particles, these will scatter light at the longer wavelengths and, because the particles are much larger than gas molecules, they will scatter it predominantly in a forward direction. Then the sky in the direction of the Sun will appear orange or red.

The red sky color indicates the presence of dust particles. Dust particles are soon washed to the surface by rain, so their presence means the air is dry, and if the air is dry, the weather must be fine. The Sun sets in the west. In mid-latitudes most weather systems travel from west to east, so a red sky seen at sunset means fine weather is approaching and will probably arrive the following day. A red sky seen in the morning is in the east, where the Sun is rising. This means the fine weather has already passed and wet weather may be approaching from the west and, if so, it will arrive within a few hours.

Further Reading

Page, Robin. *Weather Forecasting The Country Way.* London: Penguin Books, 1981.

weather map A weather map is a map that shows the distribution of AIR PRESSURE, winds, and PRECIPITATION over an area of the Earth's surface at a particular time. Weather maps that are shown on television and printed in newspapers are based on the more detailed SYNOPTIC charts used by meteorologists. There are several types, each of which is used for a special purpose.

A line on a weather map that joins points where the value of some atmospheric feature is the same is known as a contour line. Such lines have names beginning with ISO-, from the Greek work *isos,* which means equal, and they resemble the contour lines joining places at the same elevation on a topographic map. For example, isobars join points where the air pressure is the same, isohyets join points where precipitation is equal, isotherms join places where the TEMPERATURE is the same, and there are several more.

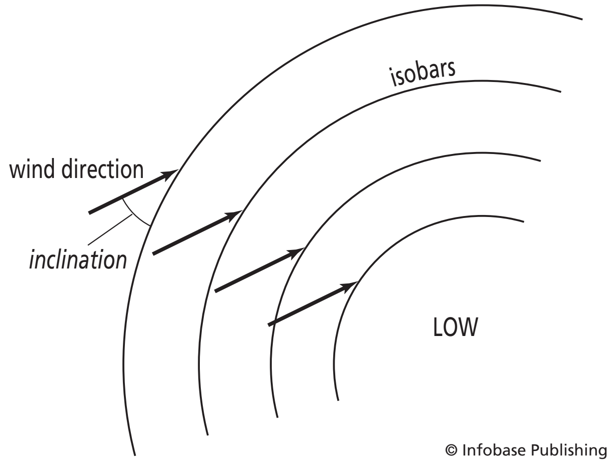
The angle shown on a weather map between the wind direction and the isobars is known as the inclination of the wind. This is an indication of the amount of FRICTION that is affecting the wind and also of the rate at which a CYCLONE is filling or an ANTICYCLONE weakening (*see* PRESSURE GRADIENT).

A normal chart, also called a normal map, is a chart on which the distribution of NORMAL values of the weather features is plotted. The chart then illustrates the average weather conditions in the area covered.

A mean chart is a weather map on which the average values for particular features are drawn as isopleths. Isopleths are lines joining points where values are the same for particular features, such as temperature, pressure, or rainfall.

A cluster map shows the weather situation over a large area, such as the coterminous United States, for a particular day. The map is prepared by a statistical technique that clusters data from many WEATHER STATIONS. This means that the reports from several stations of particular variables, such as temperature, air pressure, wind, and cloud cover, tend to be similar. These results form a cluster around a mean value. The more stations

An early weather map prepared by the Signal Service on September 1, 1872. It is reproduced from "Daily Bulletin of Weather-Reports." *(Historic NWS Collection)*



The inclination of the wind is the angle that is made between the direction of the wind and the isobars.

with data that fit into a cluster the more confidence meteorologists have in the cluster. On the final map, the generalized areas are indicated by different colors or shading to indicate the conditions within them.

A synoptic chart shows a general picture of the weather conditions over a large area at a particular time (*see* SYNOPTIC). Synoptic charts are produced at regular intervals, usually of six or 12 hours, and are based on reports from weather stations. These are plotted as STATION MODELS, and isobars are drawn to link stations where the air pressure is the same. Small differences are smoothed out, and the isobars then indicate the distribution of pressure and wind. The isobars show the reduced pressure (sea-level pressure; *see* BAROMETER) or the contours at several constant-pressure surfaces. The chart shows the CLOUD AMOUNT, surface air temperature, pressure, BAROMETRIC TENDENCY, wind direction, and wind strength. The chart also shows the surface position of cold FRONTS, warm fronts, and OCCLUSIONS.

A synoptic chart that shows the patterns of pressure, the height of pressure surfaces, temperature, wind speed and direction, or other features of the weather as these are expected to appear at some specified time in the future is called a prognostic chart or forecast chart. The position of fronts may also be drawn. If the forecast is for more than about two days ahead, the prognostic chart will show the average conditions expected, which are calculated from the range of predicted possibilities.

The center of an area of low or high pressure as these appear on a synoptic chart or other type of weather map is called the pressure center. The pressure pattern is the distribution of air pressure as it is shown by the isobars on a synoptic chart. The patterns made by the isobars indicate the location and intensity of cyclones, anticyclones, RIDGES, and TROUGHS, and the surface area that is affected by them. A pressure-change chart, also called a pressure-tendency chart, shows the barometric tendency. This is the change in air pressure that has occurred over a specified period across a surface at a constant height.

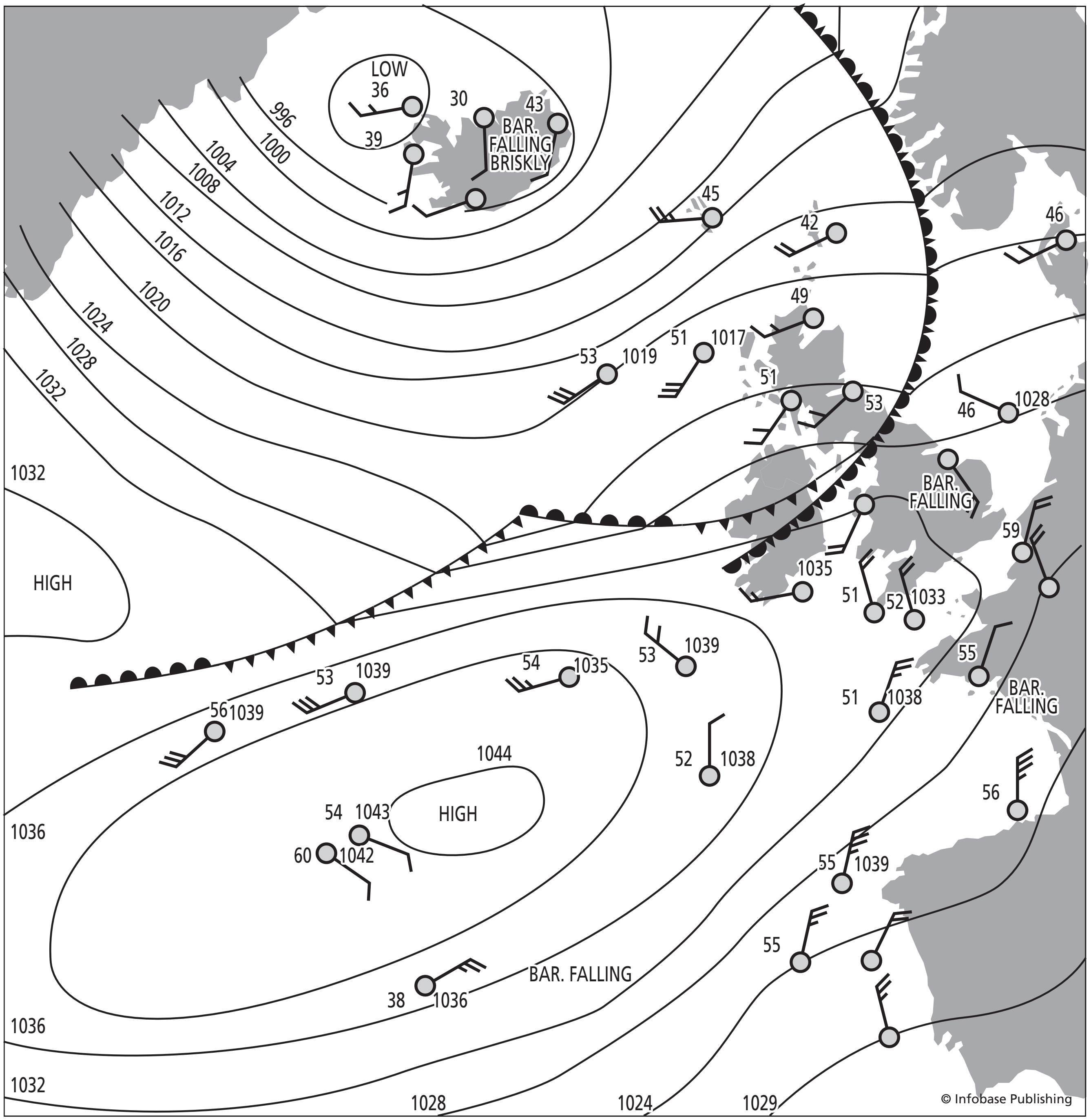
The precipitation area is the area on a synoptic chart over which precipitation is falling. Shading is often employed on TV weather maps to indicate the precipitation area. A snow-cover chart is a synoptic chart on which the areas covered by snow are marked and there are contour lines showing the depth of snow.

The synoptic scale, also called the cyclonic scale, is the scale of weather phenomena that can be shown on a synoptic chart. These events extend horizontally for about 600 miles (1,000 km), vertically for about 6 miles (10 km), and they last for about one day. These are the approximate dimensions of a cyclone. In the classification of meteorological scales that scientists use, events of these dimensions are said to occur on a meso-α scale, both spatially and temporally.

A constant-level chart is a synoptic chart on which meteorological conditions at a particular level are plotted. The level may be defined as the altitude above sea level, in which case the chart is a constant-height chart, or the level at which the atmospheric pressure remains constant, in which case the chart is a constant-pressure chart.

A constant-height chart is a synoptic chart on which the meteorological conditions at a particular altitude are plotted, based on radiosonde data (*see* WEATHER BALLOON). The heights most often used are 5,000, 10,000, and 20,000 feet (1,525, 3,050, and 6,100 m). Constant-height charts help in the identification of AIR MASSES and the boundaries between them.

A constant-pressure chart shows the distribution of atmospheric pressure, but not by means of isobars. Instead, the map assumes the existence of a level surface where the pressure is constant throughout. It then shows pressure contours that indicate heights above or below this imaginary surface. The resulting chart resembles an isobaric map and can be interpreted in the



A synoptic chart for the North Atlantic on a day in April

same way, but its lines represent heights, not pressures. It is often a more convenient way to present the data.

A center of high or low air pressure that is shown by the pattern of isobars on a constant-height chart and as an elevated or depressed region on a constant-pressure chart and that reappears on succeeding charts is called a singular corresponding point.

A surface pressure chart shows the distribution of station pressure. This is the atmospheric pressure that is measured at the surface rather than the reduced pressure, and it is indicated by isobars. An isobaric map shows the distribution of atmospheric pressure at any given height above sea level.

A tropopause chart shows the vertical distribution of pressure through the troposphere by height, isotherms, the height of the tropopause, and tropopause breaks (*see* ATMOSPHERIC STRUCTURE). An upper air chart, also called an upper-level chart, is a constant-pressure chart that depicts the condition of the atmosphere at a pressure level in the upper troposphere. Upper-air charts are usually prepared for the pressure levels at 925, 850, 400, 300, 250, 200, 150, and 100 mb. Charts are sometimes prepared for higher levels, but conditions there have little immediate effect on the weather experienced at the surface. The charts are prepared using a station model similar to those used for surface charts, but omitting information about cloud cover, precipitation, visibility, and present weather. The contour lines on a constant-pressure chart link points that are the same height above sea level.

An isentropic chart is a synoptic chart on which the elements of the weather, such as pressure, temperature, HUMIDITY, and wind, are plotted on a surface of equal POTENTIAL TEMPERATURE (an isentropic surface).

An isentropic thickness chart shows the THICKNESS of an atmospheric layer that is bounded above and below by isentropic surfaces. The thickness of such a layer is directly proportional to the convective instability (*see* STABILITY OF AIR) of the air within it. A chart that shows the difference in pressure between two isentropic surfaces is called an isentropic weight chart.

A freezing-level chart is a synoptic chart that uses contour lines to show the height of the constant-temperature surface of the FREEZING LEVEL. It shows the fronts between masses of warm and cold air and gives an indication of the likely availability of ICE CRYSTALS that may accelerate CONDENSATION, leading to precipitation.

A stability chart shows the distribution of values given by a particular STABILITY INDEX.

A vertical differential chart is a diagram that shows values for a particular atmospheric feature, such as temperature or pressure, at two different heights. A thickness chart is a vertical differential chart. A thickness chart shows the changing thickness of a particular atmospheric layer.

A föhn nose is the characteristic shape of the isobars that indicates a fully developed FÖHN WIND on a synoptic chart. There is a RIDGE on the windward side of the mountains and a föhn trough on the LEE side, producing a pattern of isobars that is reminiscent of a nose.

weather observation A weather observation is a record of weather conditions based on measurements that were made in a standardized fashion and written down according to a strict formula. This allows observations made by many people in many places to be compiled into an overall picture of weather over a large area at a certain time.

In most countries, thousands of volunteers make regular observations and communicate them to a central point. In the United States, these volunteers make up the Co-Op Network. Its members are supervised by the NATIONAL WEATHER SERVICE, which forwards the data they submit to the National Climatic Data Center. Some of the volunteers have been collecting data for more than 70 years.

A set of observations and measurements of surface weather conditions that is made at a WEATHER STATION at one of the times specified by the WORLD METEOROLOGICAL ORGANIZATION, and using standard instruments, calibrations, and methods is called a synoptic weather observation. The observations should include reduced pressure (*see* BAROMETER), TEMPERATURE, DEW point temperature, PRECIPITATION, CLOUD AMOUNT, VISIBILITY, WIND SPEED, and wind direction (*see* STATION MODEL), as well as any other details that may be relevant.

Further Reading

National Weather Service. "Cooperative Observer Program." NOAA. Available online. URL: www.nws.noaa.gov/om/coop/. Last updated February 8, 2006.

weather radar Weather RADAR is used to study processes inside clouds, especially the density of water droplets, where the water is most concentrated, and the level at which rising water droplets freeze and falling ice melts. This information is used to determine the likelihood of PRECIPITATION and the intensity of STORMS.

The technique is possible because water droplets strongly reflect electromagnetic radiation with a wavelength of 2–4 inches (5–10 cm). This was discovered early in the 1940s, but it was not until the 1960s that meteorologists first began using radar extensively. Today radar is used to monitor almost all severe storms in the United States and in many other countries.

A pattern of echoes that appears on the screen of a weather radar is known as a radar meteorological observation. The pattern reveals such features as clouds and precipitation, with their distance, density, and direction of movement. It also shows severe storms, TROPICAL CYCLONES, and TORNADOES.

Weather Radio Weather Radio comprises a network of more than 480 stations that broadcast continuous weather information 24 hours a day over the whole of the United States, U.S. coastal waters, Puerto Rico, the U.S. Virgin Islands, and the U.S. Pacific Territories. As well as ordinary information about weather conditions, the network also broadcasts warnings and watches of hazards. It also provides warnings of other types of hazard, such as volcanic activity (*see* VOLCANO), earthquakes, and chemical and oil spills.

A special radio receiver is required to pick up the signal. It is a public service provided by the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, and it broadcasts at 162.400 MHz, 162.425 MHz, 162.450 MHz, 162.475 MHz, 162.500 MHz, 162.525 MHz, and 162.550 MHz.

Further Reading

National Weather Service. "NOAA Weather Radio All Hazards." NOAA. Available online. URL: www.weather.gov/nwr/. Last updated January 31, 2006; www.nws.noaa.gov/nwr/nwrbro.htm. Accessed March 2, 2006.

weather satellite A weather satellite is a satellite that flies in Earth ORBIT and carries SATELLITE INSTRUMENTS that produce images of the Earth from which meteorological and climatological information can be obtained. Satellite images are now of vital importance in WEATHER FORECASTING and in monitoring climatic change. The first satellite dedicated to weather observation was the TELEVISION AND INFRARED OBSERVATIONAL SATELLITE (TIROS). There are now many, between them providing a complete coverage of the surface of the Earth through 24 hours every day of the year.

weather station A weather station is a place equipped with the instruments needed to make standardized measurements and observations of weather conditions and the technical and communications facilities to transmit weather reports to a central point. The station may be manned, but many modern weather stations are fully automated. An automatic weather station transmits its instrument readings to a receiving center at predetermined times without assistance. No personnel are required to operate it.

A first-order station is any weather station in the United States that is staffed partly or wholly by personnel employed by the UNITED STATES NATIONAL WEATHER SERVICE.

In the United States, a voluntary weather observer who maintains a weather station and supplies data to the U.S. National Weather Service without remuneration is called a cooperative observer. The work of such volunteers is supervised and coordinated by the Cooperative Observer Program of the National Weather Service.

A precipitation station is a weather station where only the amount and type of PRECIPITATION is measured and recorded.

A high-altitude station is one located at a sufficiently high elevation for the conditions it records to be significantly different from those at sea level. High-altitude stations are sited no lower than about 6,500 feet (2,000 m) above sea level.

A polar automatic weather station is one designed to operate in extremely cold climates. The instruments are mounted on a sled with pontoons on either side to provide additional support.

A weather ship, also called an ocean weather station, is a weather station mounted on a ship dedicated for the purpose. The ship is anchored permanently in one location (except when it needs to return to port for repairs or maintenance), and it is staffed by observers equipped with instruments to measure both atmospheric and sea conditions, which are reported to a shore station at regular intervals. Weather ships are sited away from shipping lanes, in sea areas that are not monitored by VOLUNTARY OBSERVING SHIPS. Many are in remote parts of the North Atlantic and North Pacific Oceans and the seas off Scandinavia. The requirements for an ocean weather station are laid down by the WORLD METEOROLOGICAL ORGANIZATION.

weather terms In addition to the technical terms used in METEOROLOGY, there are many informal descriptions of weather phenomena. The following list explains the meaning of a selection of popular words and expressions, arranged alphabetically for convenience.

A break is a sudden change in the weather. The term is usually applied to the ending of a prolonged period of settled dry, cold, or warm weather.

Burn-off is the clearance of FOG, MIST, or low cloud during the course of the morning, as the sunshine intensifies and the air TEMPERATURE rises. As the air grows warmer the DEW point temperature rises and suspended water droplets evaporate.

Weather conditions are sometimes said to be close, oppressive, muggy, sticky, or stuffy—all of which terms carry the same meaning. They describe a subjective feeling of discomfort that people sometimes experience when the air is still and warm (*see* COMFORT ZONE). The feeling can be experienced indoors or outdoors. It is caused by a combination of high temperature and a relative HUMIDITY that is high enough to inhibit the evaporation of sweat from the skin. The inability to cool the body by the evaporation of sweat produces an uncomfortably hot feeling and sweat that fails to evaporate soaks into clothing, which then tends to stick to the skin.

The dog days fall in July and the first half of August, which is the hottest part of the summer in the Northern Hemisphere. At this time Sirius, the brightest star in the sky, also known as the dog star, rises in conjunction with the Sun. The expression is from the Latin *caniculares dies* and arises from the Roman belief that the hot weather is due to heat from Sirius that adds to the heat from the Sun. This is not so. The amount of energy Earth receives from Sirius is infinitesimal and has no effect on the weather.

The doldrums are a sea area in which the winds are light and variable. The extent of the doldrums varies considerably with the seasons, but they are located in the INTERTROPICAL CONVERGENCE ZONE, on the side nearest the equator of the region in which the trade winds (*see* WIND SYSTEMS) originate. The calm weather of the doldrums is interrupted at intervals by fierce storms.

There are three principal doldrum zones. In the Pacific, the doldrums are located in the east, but from July to September they extend westward as a tongue reaching to about longitude 110°W. A second zone is located in the western Pacific, north of Australia and in the vicinity of Indonesia, and in the Indian Ocean. Its area increases from October to December, but it reaches its maximum extent in March and April, when it reaches from the coast of East Africa to longitude 180°E, a distance of about 10,000 miles (16,000 km). The third doldrum zone is in the eastern Atlantic. For most of the year it extends only a short distance from the African coast, but from July to September it reaches all the way across the ocean to Brazil.

Sailing ships could be becalmed in the doldrums. The variability in the location of these regions and the fact that at times they extended from one side of the Atlantic to the other made it difficult for captains to avoid them. Lack of sufficient wind to shift the vessel was a very real hazard because stores of food and drinking water could run low. Until modern times, sailors had no means of making seawater drinkable. The English poet Samuel Taylor Coleridge (1772–1834) described the plight of sailors in this condition in "The Rime of the Ancient Mariner:"

All in a hot and copper sky,
The bloody Sun, at noon,
Right up above the mast did stand,
No bigger than the Moon.

Day after day, day after day,
We stuck, nor breath nor motion;
As idle as a painted ship
Upon a painted ocean.

Water, water, everywhere,
And all the boards did shrink;
Water, water, everywhere,
Nor any drop to drink.

The origin of the word *doldrums* is obscure, but it probably comes from the Old English word *dol,* which meant dull or stupid. By early in the 19th century, a doldrum was a dull or stupid person, from which came the use of the doldrums to mean low spirits, and in the doldrums came to mean down in the dumps. Coleridge never used *doldrums* to describe the weather his Ancient Mariner experienced, because it was not until the middle of the century, after his death, that *in the doldrums* came to be associated with a geographical locality. Despite its association with the days of sailing ships, giving an impression of antiquity, it is a fairly recent word.

A dry spell is a period during which no rain falls, but that is of shorter duration than a DROUGHT. In the United States, a dry spell is said to occur if no measurable precipitation falls during a period of not less than two weeks.

The erosion of thermals is the mechanism by which a rising thermal (*see* CONVECTION) dissipates. As the warm air rises, cooler air from its surroundings is incorporated around its edges by ENTRAINMENT. The air at the edges then reaches its own equilibrium level (*see* VIRTUAL TEMPERATURE), leaving a smaller mass of air that is still rising. Entrainment continues, steadily eroding the warm air until all of it is neutrally buoyant (*see* BUOYANCY), at which stage the thermal has ceased to exist.

Exposure is the extent to which a site experiences the full effect of such meteorological events as wind, sunshine, frost, and precipitation. It is a measure of the lack of protection against the weather.

The eye of wind is the direction from which the wind is blowing or the point on the horizon from which it appears to blow. A person facing that point is said to be facing into the eye of the wind.

Fair is an adjective used to describe weather that is pleasant for a particular place at a particular time of year. The term is subjective and has no precise meaning, but it generally implies light winds, no precipitation, and less than half the sky covered by cloud.

A flurry is a sudden, brief SHOWER of SNOW that is accompanied by a GUST of wind. A mild wind SQUALL is sometimes called a flurry, even if it brings no snow.

Gloom is the condition in which daylight is markedly reduced by thick cloud or dense smoke, but horizontal VISIBILITY remains good. Gloom is not the same as anticyclonic gloom (*see* ANTICYCLONE).

Halcyon days are a period of calm, peaceful weather, especially in winter. In Greek mythology, the halcyon was a bird that laid and incubated its eggs around the time of the winter SOLSTICE in a nest that floated upon the sea. The halcyon charmed the wind and waves to make the sea calm. The mythical bird is sometimes identified with the kingfisher, and halcyon is sometimes used as a poetic name for this bird. The scientific name of the white-breasted kingfisher of North America is *Halcyon smyrnensis*.

A heat wave is a period of at least one day, but more usually lasting several days or weeks, during which the weather is unusually hot for the time of year. BLOCKING is often the cause of heat waves in middle latitudes. In North America, summer heat waves occur when the belt of prevailing westerly winds is shifted to the north. The SUBTROPICAL HIGH then expands and continental tropical air replaces maritime tropical air (*see* AIR MASS).

During a heat wave affecting much of the central United States in 1936 the temperature over parts of the Great Plains exceeded 120°F (49°C), and they reached 109°F (43°C) in several eastern states. Nearly 15,000 people died as a result of that heat wave. A heat wave in 1980 affecting Missouri, Georgia, Tennessee, and Texas brought temperatures so high that asphalt roads became plastic, concrete road surfaces expanded until they cracked and buckled, and sometimes they exploded violently. More than 1,200 people died. The highest temperatures were recorded in Memphis (108°F, 42.2°C), Augusta (107°F, 42°C), and Atlanta (105°F, 41°C). A heat wave is especially dangerous if the humidity rises as well as the temperature. Advice is available to help people protect themselves from the risks of high temperature and humidity.

Europe suffered a heat wave in August 2003, during which temperatures in France reached 104°F (40°C) and on August 10 the temperature reached 100°F (38°C) in London. A total of approximately 35,000 persons died in Europe.

The horse latitudes lie beneath the subtropical highs, centered at approximately 30°N and 30°S, where air that has risen over the equator is subsiding and diverging on the poleward side of the Hadley cells (*see* GENERAL CIRCULATION). These cells are not continuous, but where air from them is sinking to the surface the winds are light and variable and often the air is calm. Sailing ships were sometimes becalmed in these latitudes. The term *horse latitudes* refers to the fact that ships often carried cargoes of horses. When the ships were becalmed, supplies of water sometimes ran low and horses died and were thrown overboard.

The ice period is the time that elapses between the first fall of snow in winter and the melting of the last patches of snow in spring.

Indian summer is a period of warm weather with clear skies that occurs in late September and October in the northeastern United States and especially in New England. Frontal systems usually dominate the weather in early September, but late in the month these move southward and anticyclonic conditions become established. As the anticyclone extends southward, its airflow brings fine, cold weather that is followed by warm, dry air from the southwest. It is this air that produces the fine weather of the Indian summer. It is late in the year, however, and the clear skies allow the surface to cool rapidly at night by radiation, so nights are cold. There is not an Indian summer every year, and sometimes more than one occurs in a single year. A period of cool weather, with a killing FROST, must precede the warm weather for the change to be sufficiently marked to qualify as an Indian summer.

Other parts of the world also experience Indian summers. Anticyclones often become stationary over Britain in October and November, for example. They bring warm sunshine, but do not heat the ground strongly enough to produce vigorous convection resulting in cumuliform clouds (*see* CLOUD TYPES) and rain.

The origin of the term *Indian* is uncertain. It was first used in America in the 1790s and may reflect the idea that the fine weather comes from a part of the country that was then inhabited by Native Americans. The use of the term in other English-speaking countries is derived from the American usage.

The January thaw, also called the January spring, is a period of mild weather that sometimes occurs in late January in parts of the northeastern United States and in Britain. There is an English saying that "a January spring is worth nothing."

A lull is a temporary fall in the speed of the wind or cessation of PRECIPITATION.

A march is a variation over a specified period, such as the changes in weather associated with the seasons of the year, which are sometimes described as the march of the seasons. The daily march of temperature is the rhythmic cycle of temperature change in the course of 24 hours.

Persistence is the length of time during which a particular feature of the weather remains unchanged. In the case of the wind, persistence is calculated as the ratio of the mean wind vector (*see* VECTOR QUANTITY) to the average wind speed (ignoring the direction).

A rainy spell is a period during which more rain falls than is usual for the place and time of year. In Britain, the term is used more precisely to describe a period of 15 or more consecutive days during which the daily rainfall has been 0.008 inch (0.2 mm) or more.

Raw describes weather that is cold, damp, and sometimes windy.

Settled is an adjective that describes fine weather conditions that remain unchanged for a minimum of several days and more commonly for a week or more. Settled weather is usually associated with an anticyclone and is often caused by blocking.

A snap is a short period of unusually cold weather that commences suddenly.

A spell of weather is a period, usually of 5–10 days, during which particular weather conditions persist. The length of the period must be sufficient to make the spell a notable event, so it must take account of the effect of the weather on the lives of the people who experience it. A spell of fog might last only two or three days, but a spell of warm weather would need to last much longer.

A sprinkling is a very light shower of rain or snow.

Sultry is an adjective that informally describes the uncomfortable conditions that result when a high air temperature coincides with high relative humidity and still air.

The teeth of the wind is an old nautical term that means the direction from which the wind is blowing; "in the teeth of" means "in face of opposition." Sailing into the teeth of the wind meant sailing directly to windward.

Tendency is the rate of change of a vector quantity at a specified place and time.

The tendency interval is the period of time that elapses between the measurements that are used to determine the tendency of a meteorological factor. The interval is usually three hours.

A thaw is a warm spell of weather in winter or early spring during which snow and ice melt.

Unsettled is an adjective that describes weather conditions that are fine, but may change at any time in the near future with the development of cloud and possibly precipitation.

A wet spell is a prolonged period of rain. In Britain it is a spell of weather lasting for at least 15 days during which at least 0.04 inch (1 mm) of rain has fallen every day.

weather warnings National meteorological and hydrological services issue warnings of approaching severe weather. The warnings are directed to people living in the regions likely to be affected, and they are issued as far in advance as is possible. For their own safety, people hearing a warning should respond to it immediately.

Weather warnings are graded. By international agreement, warnings take a similar form throughout the world. They are graded as advisories, watches, and warnings.

An advisory means that conditions are giving cause for concern, but they are not yet severe enough to move to the next stage of alert. People should take note of an advisory and listen for any further warnings.

A watch means that conditions are such that severe weather or a hazard from water is likely to develop. The announcement specifies the type of hazard and provides as much information as is available on its intensity and direction of movement. People hearing the watch should prepare for the arrival of extreme conditions. This may include preparing to evacuate.

A warning means that the extreme conditions already exist nearby and their arrival in the designated area is imminent. It is time to take appropriate action.

In the United States the U.S. NATIONAL WEATHER SERVICE is the agency that issues weather warnings. These relate to specific threats. Advisories for each type of threat alert people to the possible risk and urge them to remain vigilant. Everyone hearing an advisory should listen to the local radio, television station, or WEATHER RADIO for further information.

A BLIZZARD watch or warning alerts people in a particular area to the imminent arrival of strong wind and heavy SNOW. This is likely to produce deep snowdrifts. VISIBILITY will be poor, possibly close to zero, and the wind will generate dangerously low WINDCHILL temperatures.

A FLASH FLOOD watch or warning alerts people to the risk of serious flash flooding. Persons receiving a flash flood watch should check their emergency supplies of food, drinking water, first aid equipment, and gasoline. On receipt of a flash flood warning they should move immediately to a place of safety. The warning may be accompanied by instructions to evacuate. Such an instruction should be obeyed immediately.

A flood watch or warning is similar to the alerts issued for flash floods, but warns of more gradual flooding than that experienced in a flash flood.

A frost-freeze warning is a little different, because freezing temperatures pose no immediate threat to human life. A frost-freeze warning to an area where cold weather is not expected informs people that the temperature is expected to fall below freezing. Some plants may be at risk and should be protected. People whose homes lack central heating should check their heaters are working and that they have adequate supplies of blankets and warm clothes.

A gale warning is a notification to shipping that winds of gale force (*see* WIND SPEED) are expected imminently in designated sea areas. The warnings are broadcast from coastal radio stations and are attached to routine weather bulletins for shipping. A gale warning is issued when a fresh gale or wind gusts of 43–51 knots (49.5–58.6 MPH; 80–94 km/h) are expected in part of a sea area, but not necessarily throughout the whole of it. A typical gale warning for the seas around Great Britain might be: "Gale warning issued by the Met Office at 0150 hours on Wednesday 1st March. Rockall, Malin, Hebrides, Bailey. Southwesterly gale force 8 imminent." The time of 0150 hours is 1.50 A.M. UNIVERSAL TIME. Rockall, Malin, Hebrides, and Bailey are the names of areas of sea around the British Isles. Force 8 is a measure on the BEAUFORT WIND SCALE and refers to a fresh gale with a wind speed of 39–46 MPH (62.7–74 km/h).

A hurricane watch or warning refers to the approach of a hurricane (*see* TROPICAL CYCLONE) to an inhabited area of the United States. The alert is issued by the National Hurricane Center, in Miami, Florida. Based on observations of the advancing storm and predictions of its future track, a hurricane watch is issued one or two days before the expected arrival of the storm. It is given to people residing in a belt of coastline and its hinterland centered on the point where it is anticipated that the storm center will cross the coast. The affected area extends for a distance equal to about three times the radius of the hurricane to either side of this point. On receipt of a hurricane watch people should prepare for the arrival of the hurricane. This includes preparation to evacuate. A hurricane warning is broadcast when the hurricane is expected to arrive within 24 hours or less. Persons receiving a hurricane warning should prepare for the imminent arrival of the hurricane and should leave a radio or television switched on and tuned to the local station. Updated information and safety instructions will be broadcast and should be obeyed promptly.

A severe THUNDERSTORM watch or warning is issued to local areas. A watch means an area may experience violent storms within the next few hours, although such storms have not yet entered the area. A warning means that violent thunderstorms have entered the area. People within the area should take immediate precautions because of an imminent risk of intense HAIL, possibly with large hailstones, LIGHTNING, winds that may GUST to 140 MPH (225 km/h), and torrential rain that may cause flooding.

A storm watch or warning provides advance information of the likelihood of severe weather. The watch or warning is of sustained winds, lasting for at least one minute, of 48 knots (55 MPH, 89 km/h) or stronger.

A TORNADO watch is issued to people living in an area where tornadoes may occur in the next few hours. Tornadoes have not yet been reported, but the conditions are right for them. A tornado warning means one or more tornadoes have been reported. Everyone in the area should immediately seek shelter.

A tropical storm watch or warning means a tropical storm is approaching an inhabited area of the United States. Based on observations of the advancing storm and predictions of its future track, a tropical storm watch is issued one or two days before the expected arrival of the storm. It is given to people residing in a belt of coastline and its hinterland centered on the point where it is anticipated that the storm center will cross the coast. The affected area extends for a distance equal to about three times the radius of the storm to either side of this point. On receipt of a tropical storm watch people should prepare for the arrival of the storm. A tropical storm warning is broadcast when the storm is expected to arrive within 24 hours or less. Persons receiving a tropical storm warning should prepare for the imminent arrival of the storm and should leave a radio or television switched on and tuned to the local station. Updated information and safety instructions will be broadcast and should be obeyed promptly.

A winter storm watch or warning is issued to alert people in a particular area to the imminent arrival of severe winter weather. A watch provides one or two days' warning of the arrival of severe weather, giving people time to prepare. The warning means conditions have already begun to deteriorate or that they will do so within the next few hours.

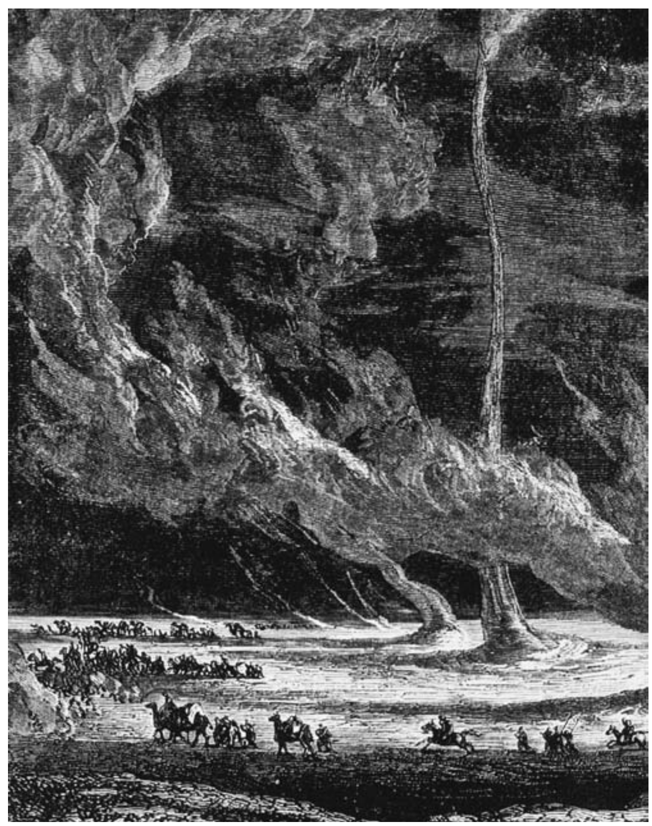
A winter weather advisory is a warning that the weather is expected to be bad enough to cause inconvenience and poor, possibly dangerous, driving conditions.

wettability Wettability is the property of a surface that has an affinity for water, because its molecules attract water molecules. The surface becomes wet as water molecules adhere to it and as the moisture penetrates the surface the substance may swell.

Seaweed is the best known wettable material. At low tide, seaweed that is exposed to the air on a beach often becomes so dry it is brittle, but it recovers at once when the incoming tide wets it once more. Small particles with this property act as CLOUD CONDENSATION NUCLEI because of their capacity for capturing molecules of WATER VAPOR.

whirlwind Although many people use the words *whirlwind* and *tornado* as though they were synonymous, in fact there are many differences between them. They are not at all the same things.

Whirlwinds appear in the desert. They rise from the SAND and DUST suddenly, without warning. There is no cloud above them, no dark, menacing sky to warn of their approach, and they are seldom alone. Where there is one, there will be several, sometimes a small army of them. Each individual lasts for only a few minutes, but as one dies another arises. In biblical times they were feared, as much for their mysterious ways as for the damage they could cause. They are much milder than true tornadoes and can do little



A whirlwind, from *The Atmosphere,* translated by James Glaisher from the work of Camille Flammarion, published in 1873. Flammarion described ". . . gigantic whirlwinds of sand which rise from the earth to the clouds. . ." *(Historic NWS Collection)*

harm to a solidly constructed building, but a whirlwind can demolish flimsy buildings and tents, and historically desert dwellers have often lived in tents.

Whirlwinds are caused by CONVECTION, as are most tornadoes, but unlike tornadoes their convection is not sustained by the LATENT HEAT of CONDENSATION. They occur in dry air and there is no condensation of WATER VAPOR.

Desert whirlwinds develop on calm days, when there is little or no wind. Wind mixes the air, so that if the ground surface is hotter in one place than it is in another the air in contact with the hot ground will be mixed with cooler air from nearby. This mixing does not happen on still days, however, and because the desert surface is uneven, with some areas exposed to full sunshine and others shaded, and because it is made of a variety of materials, it heats unevenly. By early afternoon patches of exposed rock can be 30°F (17°C) hotter than nearby sand, because of differences in their ALBEDOS and HEAT CAPACITIES.

Air over the hot spots is heated by contact with the surface. The air expands and rises by convection, creating a small region at the base where the AIR PRESSURE is very slightly lower than it is farther away. Air from all sides is drawn into the low-pressure area, and as the air converges (*see* STREAMLINES) its VORTICITY makes it start to rotate. As it approaches the center, the air accelerates in order to conserve its angular MOMENTUM. Then it is warmed and rises. Air is then spiraling inward and upward. This is very like a tornado, but it is driven from below rather than from a storm cloud overhead.

The spiraling air is made visible by the dust and sand that is carried into its VORTEX and then high into the sky. Although the pressure at its center is low, the relative HUMIDITY is too low for water vapor to condense. The lack of water vapor also limits the lifespan of a whirlwind. It has no source of additional heat above ground level to maintain the upward flow of air. At the same time, relatively cool air flowing into the base of the vortex cools the hot ground, so before long the ground is at the same temperature as the surrounding surface. Air ceases to be drawn into the area and the whirlwind dies. The strongest whirlwinds can last for several hours, but many last for only a few seconds.

Whirlwinds vary in size. Most rise to about 100 feet (30 m). Some reach 300 feet (100 m), and a few grow to 6,000 feet (1,800 m) tall.

Further Reading

Allaby, Michael. *Tornadoes*. Rev. ed. Dangerous Weather. New York: Facts On File, 2004.

whiteout Whiteout is the condition in which the ground, air, and sky are all a uniform white and no landscape features are visible. Persons exposed to a whiteout lose their perception of depth and quickly become disoriented, so a whiteout is extremely dangerous.

There are two ways in which a whiteout can occur. In calm weather, a uniformly white SNOW surface may lie beneath low cloud. The cloud diffuses light passing through it, so light falls on objects evenly from all sides and there are no shadows. Consequently, everything appears white. If dark objects are visible, they appear to float and it is impossible to determine their distance.

Whiteout can also occur in a BLIZZARD. Again the light is diffused by clouds, but in this case there are also SNOWFLAKES between the CLOUD BASE and the ground. The snowflakes are tumbling and turning in all directions, reflecting light in all directions as they do so. A flashlight is useless in the second type of whiteout, because the light is scattered by the falling snowflakes, and so much may be reflected back to the person with the flashlight that it becomes dazzling.

Further Reading

Allaby, Michael. *Blizzards*. Rev. ed. Dangerous Weather. New York: Facts On File, 2004.

Wien's law Wien's law is a physical law that describes the relationship between the TEMPERATURE of a BLACKBODY and the wavelength (*see* WAVE CHARACTERISTICS) of its maximum emission of radiation. The wavelength varies inversely with the temperature (the higher the temperature the shorter the wavelength), and the law can be stated as:

$$\lambda_{max} = C/T$$

where λ_{max} is the wavelength of maximum emission, C is Wien's constant, and T is the temperature in kelvins. Wien's constant is 2897×10^{-6}m (2,897 μm), so the law becomes:

$$\lambda_{max} = (2897 \times 10^{-6}\text{m})/T$$

Wien's law is valid only for radiation at short wavelengths. The law was discovered in 1896 by the German physicist Wilhelm Wien (1864–1928; *see* Appendix I: Biographical Entries) and for it he was awarded the 1911 Nobel Prize in physics.

wilting Wilting is the limpness that occurs when the cells of a plant contain insufficient water to keep them rigid. The leaves droop and a nonwoody plant may collapse.

Wilting may occur when the rate of transpiration exceeds the rate at which water is able to enter the root system of the plant from a soil containing abundant water. In this case the wilting is temporary, and the plant will recover when the transpiration rate decreases.

Wilting may also be due to a deficiency of water in the soil, in which case the plant will not recover unless it is given water. The percentage of water that remains in the soil after a test plant has wilted is known as the permanent wilting percentage (also called the permanent wilting point, wilting coefficient, and wilting point).

Wilting also occurs when the vessels of a plant are blocked, often by a fungal infection, or when water is being taken from the plant vessels by a parasite. Wilting due to infection is called wilt.

wind Wind is the movement of air that results from an uneven distribution of air pressure. Air tends to move from regions of high pressure to regions of low pressure at a speed that is proportional to the pressure gradient. It does not flow directly from the center of high pressure to the center of low pressure, however, owing to the Coriolis effect caused by the rotation of the Earth (*see* geostrophic wind). Local effects also produce winds such as föhn winds, anabatic winds, and katabatic winds that occur near mountains (*see also* avalanche), lake breezes, and land and sea breezes. Winds are generally thought of as blowing horizontally, but they can also have a vertical component.

A wind field is a pattern of winds associated with a particular distribution of pressure. Wind stress is the force per unit area that is exerted on the land or water surface by the movement of air.

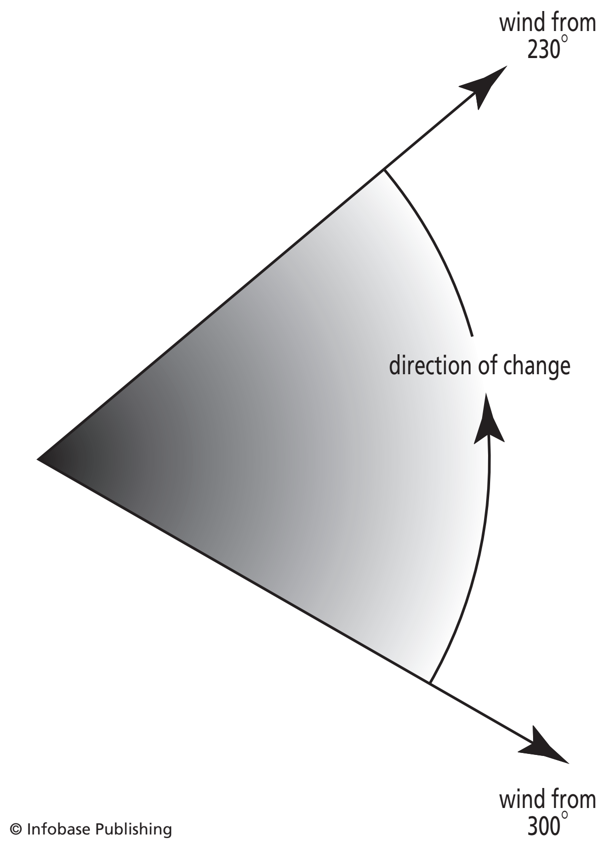
The wind direction is always given as the direction from which the wind blows (and *not* the direction in which it is blowing). The reason for this is historical (*see* Tower of the Winds). Wind direction is measured by a wind vane or aerovane. The wind direction as measured by a magnetic compass is known as the magnetic wind direction. The compass indicates the direction of the magnetic North Pole, which is located in the islands of northern Canada, at approximately 77.3°N 101.8°W (the magnetic South Pole is at approximately 65.8°S 139.0°E). Consequently, the magnetic wind direction is not the same as the wind direction measured in relation to true or geographic north. The difference between the direction of magnetic north and south and true north and south, called the magnetic declination, varies at different positions on the Earth's surface and at different times (because the magnetic poles move). Wind vanes are usually oriented to geographic north and south, so they indicate the true wind direction. A person who is told the wind direction as it is indicated by a wind vane and who needs to apply this information using a magnetic compass (for example, a sailor at sea or the pilot of an airplane) must remember to make the necessary correction.

The weather shore is the shore from which the wind is blowing, as seen by a ship at sea. The weather side of a ship is the side that faces into the wind or weather. Windward is the side that faces the direction from which the wind is blowing.

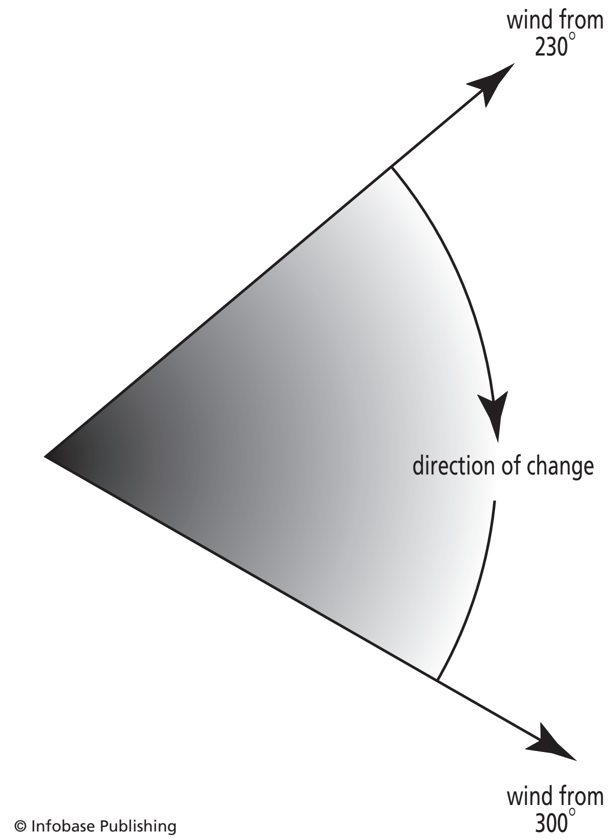
A wind-shift line is a boundary that marks a large and abrupt change in the wind direction. Backing is any change in the wind direction (not necessarily a large or abrupt one) that moves in a counterclockwise direction, for example from the northwest to the southwest. If the wind direction is given as the number of degrees counting clockwise from north, a backing wind decreases the number. Veering is a change in the wind direction that moves in a clockwise direction, for example from the southwest to the northwest. If the wind direction is given as the number of degrees from north, a veering wind increases the number.

The surface wind is the speed and direction of the wind that blows at the surface of land or sea. In order to minimize the deflection of the wind by trees, buildings, and similar obstacles, the instrument used to measure the surface wind is mounted on a pole or tower at least 33 feet (10 m) tall.

The spot wind is the wind that is observed or forecast at a specified height over a specified location. The resultant wind is the average speed and direction of the wind at a particular place over a specified period. It is calculated by recording the wind speed and direction at



Backing is a change in the wind direction in a counterclockwise sense, in this case from 300° to 230°.



Veering is a change in the wind direction in a clockwise sense, in this case from 230° to 300°.

intervals throughout the period, then calculating their mean values.

A planetary wind is any wind that has a speed and direction caused wholly by the interaction of solar radiation and the rotation of the Earth.

A windbreak is a wall, fence, or other structure that is erected for the purpose of slowing or deflecting the wind.

A windrow consists of loose material that has accumulated naturally to form a line. If it occurs inland or on the surface of the open sea or a lake, the material has been arranged by the wind and the orientation of the line indicates the wind direction. If the windrow occurs on a beach, it has been formed by the action of the TIDES.

windchill Windchill describes the extra feeling of cold that a person experiences when exposed to the wind. The effect can be measured, and its magnitude is usually reported in degrees Fahrenheit (or Celsius). This gives the misleading impression that when a wind is blowing the air TEMPERATURE actually falls, which is obviously wrong. Wind is simply moving air; that it moves does not alter its temperature.

The confusion arises because of the use of temperature units. These are familiar and therefore easy to understand, but what happens when people are exposed to the wind is that heat energy is removed from their body surfaces. A person's internal body temperature changes very little, and a drop of just a few degrees can be fatal. Heat and temperature are not the same thing and different units are used to measure them. Scientists measure heat in joules, calories, or less commonly in British thermal units (*see* UNITS OF MEASUREMENT). These units are more difficult to understand than degrees, and so temperature units are used.

People keep warm in winter by wearing clothes. These trap a layer of air. The heat of the body warms this air and, once it is warm, the air provides insulation. If someone goes outdoors into air that is much colder than body temperature, the layer of warm air inside clothes protects him or her, and the clothes themselves keep the warm air in place.

If the person goes out into a wind, however, the moving air may penetrate the clothing and blow away some of the protective layer of warm air. As warm air disappears, the body must work harder to replace it. Blood vessels near the body surface contract. This reduces the rate at which the blood is cooled by passing through cold tissues. Then stamping the feet, rubbing the hands, beating the arms, eventually shivering all involve rapid muscular movements that generate heat. If the wind is strong enough, however, it may remove warm air faster than the body can either replace it by generating more heat or compensate for its loss. That is when people start to feel cold. How cold they feel depends on the temperature of the air and the speed of the wind.

The rate at which a human body loses heat through windchill increases rapidly as the temperature drops and the wind speed rises, until the wind speed reaches about 40 MPH (64 km/h). At wind speeds faster than this there is only a small increase in windchill.

It is heat that the body is losing, measured in joules or calories, but the effect of the wind is to cool the body at the rate it would chill if the temperature were lower. For anyone going outdoors on a still day when the temperature is 10°F (-12°C), that is how cold it will feel. If there is a wind blowing at 10 MPH (16 km/h), however, the body will lose heat at the same rate as it would on a day with no wind, but with an air temperature of -9°F (-23°C). The effect of windchill does not alter the actual temperature of the air, but it does lower the effective temperature, because it removes some of the insulating layer of warm air and so increases the rate at which the body loses heat.

People need more protection against the cold on a windy day than they do on a still day. When the temperature is below about -21°F (-29°C) on a day with no wind, they need to be well wrapped up, with no bare skin exposed. If there is a wind, that effective temperature will be reached at a much higher actual temperature. With a gentle wind of 5 MPH (8 km/h) the effective temperature will be -21°F (-29°C) when the actual air temperature is -15°F (-26°C). If the wind speed is 25 MPH (40 km/h), that effective temperature is reached when the air temperature is +15°F (-9°C).

Wind chill temperature (°F)

Wind speed (mph)

0	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40
5	32	27	22	16	11	6	0	-5	-10	-15	-21	-26	-31	-36	-42	-47
10	22	16	10	3	-3	-9	-15	-22	-27	-34	-40	-46	-52	-58	-64	-71
15	16	9	2	-5	-12	-18	-25	-31	-38	-45	-51	-58	-65	-72	-78	-85
20	12	4	-3	-10	-17	-24	-31	-39	-46	-53	-60	-67	-74	-81	-88	-95
25	8	1	-7	-15	-22	-29	-36	-44	-51	-59	-66	-74	-81	-88	-96	-103
30	6	-2	-10	-18	-25	-33	-41	-49	-56	-64	-71	-79	-86	-93	-101	-109
35	4	-4	-12	-20	-27	-35	-43	-52	-58	-67	-74	-82	-89	-97	-105	-113
40	3	-5	-13	-21	-29	-37	-45	-53	-60	-69	-76	-84	-92	-100	-107	-115

To calculate the windchill, find the actual air temperature in the top row of figures. Then find the wind speed in the vertical column on the left. Follow the figures along the row and column, and the figure where they intersect is the effective temperature due to windchill. The lightly shaded figures indicate temperatures that are dangerously low. The dark shading indicates temperatures that are extremely dangerous.

Weather reports and forecasts (*see* WEATHER FORECASTING) always include wind speeds, and in winter they often include the "windchill factor," but it is simple to work this out using the table at the bottom of page 551. First, though, it is necessary to correct the reported wind speed. Meteorologists measure wind speed well clear of the ground. Close to the ground the wind is slowed by FRICTION, especially in towns, and allowance must be made for this. Unless the report clearly states that the figure quoted refers to the wind speed at ground level, assume the wind speed at ground level will be about two-thirds of the reported speed.

When the effective temperature falls below about -71°F (-57°C), conditions are extremely dangerous. Anyone whose body starts to lose heat in this actual or effective temperature is liable to lose consciousness and die within a short time.

Further Reading

Allaby, Michael. *Blizzards*. Rev. ed. Dangerous Weather. New York: Facts On File, 2004.

wind power Wind power is energy obtained by harnessing the wind to perform useful work. Sails are probably the most ancient example. These were being used to propel boats along the River Nile possibly as early as 4000 B.C.E.

The earliest windmills were built in Persia (Iran) in the seventh century C.E. They were based on designs that were already used for watermills. By the 13th century, windmills were appearing in many parts of Europe, their development having been strongly encouraged by the Mongol leader Genghis Khan.

Until recently, mills were used principally for grinding cereal grains to make flour and meal, or to pump water. The first windmill to generate electrical power was built in Denmark in 1890. One of the first experimental large-scale wind generators was built on the top of Grandpa's Knob, a hill near Rutland, Vermont. Construction of the generator began late in 1940, and it commenced operation in 1941, with a rated generating capacity of 1.25 MW. The generator ran for 1,000 hours over the next 18 months, operating in winds of 70 MPH (113 km/h), and it survived winds of 115 MPH (185 km/h). During this time several repairs and modifications were made to the structure. The generator was taken out of service in February 1943 due to the failure of a main bearing, and the replacement bearing was not installed until March 3, 1945. On March 26, 1945, one of the 75-foot (23-m), 8-ton (7.3-tonne) rotor blades broke free in a 20-MPH (32-km/h) wind. The blade came to rest on its tip, 700 feet (214 m) down the hillside. The generator was never repaired.

The generation of electrical power is now the principal use for windmills. A modern "windmill," more properly known as a wind turbine, comprises rotor blades or sails. In the horizontal-axis design, which is the one most widely used, the blades are shaped as aerofoils with adjustable pitch—each blade can be turned on its own axis, thus altering the angle at which it meets the air. The horizontal axis to which the rotors are attached is free to turn on a vertical axis. This allows the blades to face into the wind at all times. Vertical-axis mills have sails held on radial arms.

The power that can be derived from the wind depends on the WIND SPEED, the DENSITY of the air, and the area of the circle described by the rotor blades. It can be calculated from the equation:

$$P = 0.5\rho AV^3$$

where P is the power, ρ is the air density (about 0.08 pounds per cubic foot, 1.225 kg/m^3 at sea level, but less at higher elevations), A is the area swept by the rotor in square meters, and V is the wind speed in meters per second.

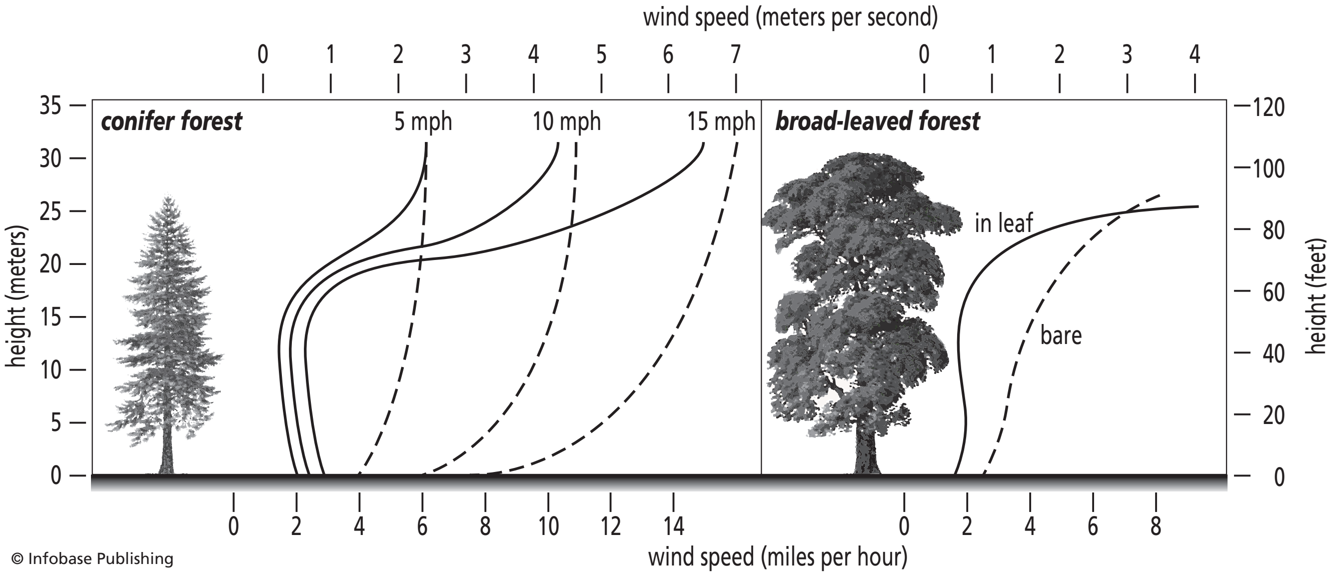
The proportion of this power that a wind turbine is able to extract is given by:

$$P = 0.5\rho AC_pV^3N_gN_b$$

where C_p is the coefficient of performance of the rotor (a theoretical maximum value of 0.59, but an actual value of 0.35 or less), N_g is the efficiency of the generator (from 0.5 to 0.8), and N_b is the efficiency of the gearing and bearings (up to 0.95). P is in watts (746 W = 1 horsepower; 1,000 W = 1 kilowatt; 1,000 kW = 1 megawatt).

A wind farm comprises a number of wind turbines that are sited at the same location. Each turbine generates electrical power and the combined output from all the turbines at the farm is fed into the public power supply.

Wind farms may comprise as few as 10 turbines or as many as several hundred, and the rated capac-



This wind profile diagram compares the change of wind speed with height in a conifer forest (left) and a broad-leaved forest (right). In both cases, wind speed increases sharply above the forest canopy. The broken lines in the diagram of the conifer forest show the wind speed over open ground. The two lines in the diagram of the broad-leaved forest compare the effect of the trees when bare and in full leaf.

ity of the individual turbines varies from about 450 kW to 5 MW. The largest wind farm in Australia is at Esperance, Western Australia. It has nine turbines and a rated capacity of 2 MW. The German Land (state) of Schleswig-Holstein is planning to build the biggest wind farm in Europe. It will be located in North Sea coastal waters near Helgoland, where it will occupy 77 square miles (200 km^2) and have a rated capacity of 1,200 MW. On December 1, 2005, the Bundesamt für Schiffahrt und Hydrografie (Federal Authority for Navigation and Hydrography) approved the construction of the first phase of 80 turbines. The farm is scheduled for completion in 2008. Smaller offshore wind farms are also planned for the North and Baltic Seas.

wind profile A wind profile is a diagram that shows the change in wind characteristics with height and horizontal distance. A wind speed profile, based on measurements, can be used to show the effect on the wind of an obstruction, such as a tree. The profile can then help in designing buildings or SHELTER BELTS. The wind speed at any height in the profile is given by

$$u = (u*/k) \ln (z/z_o)$$

where u is the wind speed, $u*$ is the friction velocity, k is the von Kármán constant, z is the height above the surface, z_o is the roughness length (*see* AERODYNAMIC ROUGHNESS), and ln means the natural logarithm.

A logarithmic wind profile shows the variation of wind VELOCITY with height throughout the PLANETARY BOUNDARY LAYER, but above the laminar BOUNDARY LAYER. This is expressed by an equation:

$$\overline{u_z} = (u*/k) \ln (z/z_0)$$

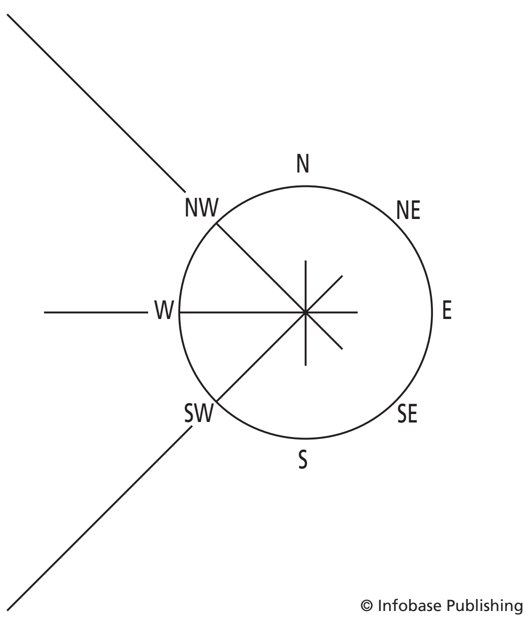
where $\overline{u_z}$ is the mean wind speed in meters per second at a height z, $u*$ is the friction velocity, k is the von Kármán constant, and z_0 is the roughness length in meters.

The friction velocity, also known as the shear velocity, is the velocity of air in the planetary boundary layer, but above the laminar boundary layer. It is symbolized by $u*$ and is equal to $(\tau/\rho)^{1/2}$, where τ is the tangential stress on the horizontal surface and ρ is the density of the air.

The von Kármán constant is a value that was discovered by the Hungarian-born American aerodynamicist Theodore von Kármán (1881–1963). Its value is approximately 0.4. The von Kármán constant holds under all circumstances, but the difficulties involved in wind experiments make it impossible to measure it precisely.

A wind profiler is a ground-based instrument that measures the wind speed at different heights and at frequent intervals. Profilers measure the wind through the whole of the troposphere and the lower stratosphere (*see* ATMOSPHERIC STRUCTURE), with a vertical resolution ranging from about 200 feet (61 m) to about 3,300 feet (1 km), taking readings as frequently as every six minutes. The instrument works by Doppler RADAR. It transmits one radar beam vertically and, depending on the instrument type, two to four others at an angle of about 75° with respect to the horizon. The pulses, at a frequency of 900–1,500 MHz, are reflected by turbulent EDDIES. These move with the wind and consequently the reflected beams are Doppler-shifted. The Doppler shift can be interpreted as the speed of the wind crossing from one beam to another, and the time that elapses between the transmission of the beam and reception of its reflection indicates the height above the instrument.

wind rose A wind rose is a diagram that shows the frequency with which the wind at a particular place blows from each direction. This reveals the direction of the prevailing wind (*see* WIND SYSTEMS). The wind rose is constructed from measurements of the wind direction that are made from the same point at the same time every day.



Each of the straight lines represents a direction from which the wind blows. The length of each line indicates the frequency with which it blows from that direction. In this case, the prevailing winds are from the southwest or northwest.

At the end of the recording period, which is often one calendar month, the daily wind directions are grouped into eight general compass directions: N, NE, E, SE, S, SW, W, and NW, according to which is nearest. They are then drawn as lines originating from a point, with north at the top of the drawing. The direction of each line is that of the wind and it is drawn to a convenient unit of length, such as 0.25 inch (6 mm). If the same direction occurs on another day, the line is made one unit longer. When the rose is complete, it will indicate the comparative frequency of each wind direction and therefore the prevailing wind for that period. The diagram also contains a circle, the radius of which is drawn to the same scale as the wind lines and represents the frequency of days on which the air was calm. The data can also be used to construct wind roses for each season and for the year. Obviously, the longer the record the more reliable the wind roses are likely to be.

Wind roses are very useful aids to planning. Foresters need to take account of prevailing winds when designing plantation forests in order to minimize damage from BLOWDOWN. The design of an urban development also needs to allow for the wind, to avoid the urban canyon (*see* URBAN CLIMATE) effect and exposing open spaces to winds funneled into them (*see* WIND SPEED) along streets.

Wind roses are also used in planning airports so that their main runways can be aligned with the prevailing wind. This reduces the length of takeoff and landing runs. On takeoff it is the speed of the airflow over the wings of an aircraft that determines the amount of lift that is generated. If the aircraft takes off into the wind, that speed is equal to the sum of the forward speed of the aircraft and the speed of the wind, thus reducing the time it takes for the aircraft to attain the speed needed to become airborne. On landing, a headwind has a strong braking effect.

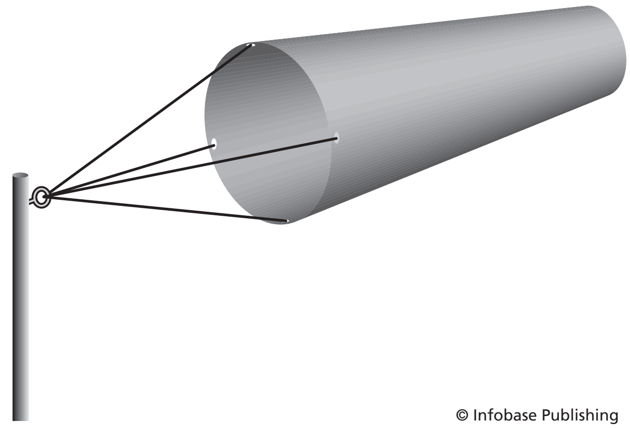
wind shear Wind shear is a change of wind VELOCITY with vertical or horizontal distance. FRICTION occurs between adjacent bodies of air that are moving in different directions or at different speeds. Where the difference is in speeds rather than direction, this tends to accelerate the slower air and retard the faster air until both are moving at the same speed. Over land this would cause the wind to cease because of friction between the lowest layer and the ground, and over the sea it would reduce the wind speed to the speed of the surface waves. This rarely happens because the wind is usually driven by a large-scale weather system or by prevailing winds (*see* wind systems) acting at some distance above the surface, and because random movements of air molecules cause air to intermingle at the boundary between the two bodies of air. The molecules also transfer their momentum, and this distributes the force driving the wind.

Above the level at which friction with the surface exerts an effect the amount of wind shear varies according to the way the air temperature changes and it gives rise to the thermal wind. Where a strong upper-level wind blows across a slower lower-level wind the effect can be to start a column of rising air rotating about a vertical axis. This is the mechanism by which a mesocyclone is formed, in extreme cases leading to a tornado.

Anticyclonic wind shear is horizontal wind shear that produces an anticyclonic (*see* anticyclone) flow in the air to one side of it. Cyclonic wind shear is associated with vorticity around cyclones. Looking downwind, the winds are stronger on the right in the Northern Hemisphere and on the left in the Southern Hemisphere. This tends to set the air rotating cyclonically along the line of the wind.

wind sock A wind sock is a simple device for indicating the direction of the wind that was once a feature of every airfield and that is still seen at the smaller airfields used by light aircraft. It consists of a tapering cylinder of fabric that is open at both ends and supported on a circular frame at the larger end. The sock is attached by cords to the top of a tall pole. It fills in the slightest wind and, being free to turn in any direction, it indicates the wind direction. Unlike a wind vane or aerovane, a wind sock also indicates an absence of wind; when the air is calm the sock hangs limply.

Windsocks are usually colored bright yellow or orange to make them more visible and they can be seen clearly from the air. They were especially useful in the days before airfields had runways and aircraft landed and took off from a grass surface because they made it possible for the pilot to turn the aircraft into the wind.



A wind sock, made of fabric, is free to turn in any direction at the top of its pole. It can be seen clearly from the air.

wind speed The wind speed is the rate at which the air is moving. This is measured using an anemometer or aerovane and the measurement is of speed only, and takes no account of the wind direction (unlike wind velocity).

Wind velocity is the speed and direction of the wind when these are reported together. Velocity is a vector quantity and consequently comprises two values. Wind velocity is reported in the form: direction/speed. Direction is reported in degrees, counting clockwise from north, which is 0°, but usually with the degree sign omitted. East is 090, south is 180, and west is 270. For example, a report to an aircraft might describe the wind as 240/30, meaning that the wind is blowing from 240° at 30 knots (*see* units of measurement). Scientists usually report wind speed in meters per second, so in this example the wind would be 240/15.

There are several ways in which wind speed may be reported, depending on the purpose for which the report is issued. Ships are usually informed of the wind force on the Beaufort wind scale. Hurricanes and other types of tropical cyclone are allotted categories on the Saffir/Simpson hurricane scale that indicate the sustained wind speeds associated with them. Tornado speeds are re ported using the Fujita tornado intensity scale. Some public weather forecasts give the wind as a force on the Beaufort scale, but most use miles per hour (MPH) or kilometers per hour (km/h). Reports to aircraft use knots. Meteorologists usually use meters per second (m/s). To convert these units:

1 MPH = 1.619 km/h = 0.87 knot = 0.45 m/s

1 knot = 1.15 MPH = 1.85 km/h = 0.51 m/s

1 km/h = 0.6214 MPH = 0.54 knot = 0.28 m/s

1 m/s = 2.24 MPH = 1.95 knot = 3.6 km/h

The scientific measurement of wind speed is called anemometry. Speed is the distance a body travels in a unit of time. It is not practicable, however, to label a small volume of air in order to make it visible and then to time its movement over a measured distance. Instead, it is necessary to measure the speed indirectly, by the effect the wind has at different speeds on visible objects. The first successful method was the one devised by Admiral Sir Francis Beaufort (*see* APPENDIX I: BIOGRAPHICAL ENTRIES). In the earliest version of the Beaufort wind scale, all the wind forces, including gales, were described in terms of their effect on sailing ships and speeds were not allotted to them. The advantage of the Beaufort wind scale is that in its modern version, with wind speeds added, it is based on the response of commonplace objects, such as smoke, flags, trees, and umbrellas. Consequently, it requires no instruments. The Beaufort scale is still used. Weather stations use anemometers to measure wind speed.

The peak gust is the highest wind speed that is recorded at a WEATHER STATION during a period of observation, commonly of 24 hours. Despite the name, a peak gust may be a sustained wind rather than a GUST.

The fastest mile is the greatest wind speed, measured in miles per hour, recorded over a specified period (usually 24 hours) for one mile of wind. A mile of wind is calculated from the number of rotations of a rotating-cups anemometer during a measured interval of time. If each cup is at a distance x from the axis of the anemometer, then in each revolution it travels a distance of $2\pi x$. If the cup completes n rotations in an hour, during that hour it travels a total distance of $n(2\pi x)$. When the distance is converted to miles, it represents the number of miles of wind.

A first gust is a sudden sharp increase in the wind speed that is felt as a cumulonimbus cloud (*see* CLOUD TYPES) enters its mature stage. The gust is caused by the arrival at the surface of the cold downdraft.

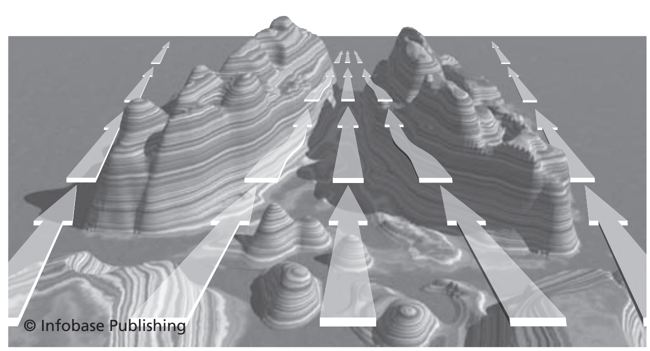
Funneling is an acceleration of the wind that occurs when moving air is forced through a narrow passage. A funneling effect is felt when the wind direction is approximately parallel to the axis of a deep, narrow valley or a street lined by tall buildings (*see* URBAN CLIMATE). Although the wind is retarded to some extent by FRICTION, the fact that the rate at which air leaves the valley or street must be equal to the rate at which it enters means the flow must accelerate as it passes the constraint. At the same time, the AIR PRESSURE decreases in proportion to the acceleration, due to the BERNOULLI EFFECT.

In the Beaufort wind scale, calm is wind force 0, which is the condition in which the wind speed is 1 MPH (1.6 km/h) or less. The air feels calm and smoke rises vertically.

The threshold velocity is the minimum speed at which wind raises DUST, soil, or SAND particles from the ground. This speed varies according to the size of the particles and the amount of moisture because water adhering to mineral grains holds them together.

In the Beaufort wind scale, light air is force 1. This is a wind that blows at 1–3 MPH (1.6–5 km/h). In the original scale, devised for use as sea, a force 1 wind is just sufficient to give steerage way to a sailing ship. On land, wind vanes and flags do not move, but rising smoke drifts.

A breeze is a light wind. In the Beaufort wind scale, a breeze is a wind blowing at 4–31 MPH (6.4–49.8 km/h). Within this range, breezes are classified as light, gentle, moderate, fresh, and strong. A puff of wind is a breeze that is just strong enough to produce a patch of ripples on the surface of still water.



Funneling occurs when the sides of a valley or buildings lining a street constrict the air flowing parallel to the valley or street, causing it to pass through a smaller passageway in the same amount of time.

In the original Beaufort wind scale, devised for use at sea, light, gentle, and moderate breezes, winds of force 2–4, were defined as "or that in which a man-of-war with all sail set, and clean full would go in smooth water from."

A light breeze is force 2 in the Beaufort wind scale. This is a wind that blows at 4–7 MPH (6.4–11.3 km/h). On land, a light breeze is just strong enough for drifting smoke to indicate the wind direction.

A gentle breeze is force 3 in the Beaufort wind scale. This is a wind that blows at 8–12 MPH (13–19 km/h). On land, a gentle breeze makes leaves rustle, small twigs move, and flags made from lightweight material stir gently.

A zephyr is any very gentle breeze, but especially one that blows from the west. Zephuros was the Greek god of the west wind, and Zephiros, from which *zephyr* is derived, was the Latin version of the name.

A moderate breeze is force 4 in the Beaufort wind scale. This is a wind that blows at 13–18 MPH (21–29 km/h). On land, a moderate breeze causes loose leaves and dry scraps of paper to blow about.

A fresh breeze is force 5 in the Beaufort wind scale. This is a wind that blows at 19–24 MPH (31–37 km/h). In the original scale, devised for use at sea, a force 5 wind was defined as "or that to which a well-conditioned man-of-war could just carry in chase, full and by." On land, a fresh breeze makes small trees that are in full leaf wave about.

A strong breeze is force 6 in the Beaufort wind scale. This is a wind that blows at 25–31 MPH (40–50 km/h). In the original scale, devised for use at sea, a force 6 wind was defined as "or that to which a well-conditioned man-of-war could just carry single-reefed topsails and top-gallant sail in chase, full and by." On land, it is difficult to use an open umbrella in a strong breeze.

A gale is a strong wind, ranging from one that exerts strong pressure on people walking into it to one that breaks and uproots trees. On the Beaufort wind scale there are four categories of gale: moderate gale (force 7), fresh gale (force 8), strong gale (force 9), and whole gale (force 10). A wind stronger than a whole gale is called a STORM, and one weaker than a moderate gale is a strong breeze.

In the original Beaufort wind scale, devised for use at sea, moderate and fresh gales, wind forces 7, were defined as "or that to which a well-conditioned man-of-war could just carry in chase, full and by."

A moderate gale is force 7 in the Beaufort wind scale. This is a wind that blows at 32–38 MPH (51–61 km/h). On land, people walking into the wind feel it exerting a strong pressure in a moderate gale.

A fresh gale is force 8 in the Beaufort wind scale. This is a wind that blows at 39–46 MPH (63–74 km/h). On land, a fresh gale tears small twigs from trees.

A strong gale is force 9 in the Beaufort wind scale. This is a wind that blows at 47–54 MPH (76–87km/h). In the original scale, devised for use at sea, a force 9 wind was defined as "or that to which a well-conditioned man-of-war could just carry close-reefed topsails and courses in chase, full and by." On land, slates and tiles are torn from roofs in a strong gale and chimneys are blown down.

A whole gale is force 10 in the Beaufort wind scale. This is a wind that blows at 55–63 MPH (88–101 km/h). In the original scale, devised for use at sea, a force 10 wind was defined as "or that with which she could scarcely bear close-reefed main topsail and reefed foresail." On land, a whole gale breaks or uproots trees.

A storm is force 11 in the Beaufort wind scale. This is a wind that blows at 64–75 MPH (103–121 km/h). In the original scale, devised for use at sea, a force 11 wind was defined as "or that which would reduce her to storm staysails." On land, a storm uproots trees and blows them some distance, and overturns cars.

A hurricane-force wind is force 12, the highest value on the Beaufort wind scale, with a wind speed in excess of 75 MPH (121 km/h). This wind speed defines a category 1 hurricane on the Saffir/Simpson hurricane scale. In the original scale, devised for use at sea, a hurricane-force wind was described as "or that which no canvas could withstand."

wind systems Many regions of the world experience winds of particular types or from particular directions. These are not LOCAL WINDS, because their effect is felt over large areas. They are prevailing winds, and many of them have names.

A prevailing wind is one that blows more frequently from one direction than from any other. In middle latitudes, for example, the prevailing winds are westerlies, which means they blow from the west. Winds in the TROPICS usually blow from the east, so there the prevailing winds are easterlies. A WIND ROSE is compiled to determine the direction of the prevailing wind.

The trade winds are the most reliable of all prevailing winds. These winds blow toward the equator from either side, from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. They are extremely dependable, especially on the eastern side of the Atlantic, Pacific, and Indian Oceans, blowing at an average speed of about 11 MPH (18 km/h) in the Northern Hemisphere and 14 MPH (22 km/h) in the Southern Hemisphere.

Air rises over the INTERTROPICAL CONVERGENCE ZONE (ITCZ). When it reaches the tropopause (*see* ATMOSPHERIC STRUCTURE), the air moves away from the equator, and it subsides in the Tropics. As it descends into the SUBTROPICAL HIGHS, some of the air flows away from the equator into higher latitudes, but most of it flows back toward the equator. It is joined by air flowing toward the equator from outside the Tropics. This circulation of air comprises the Hadley cell (*see* GENERAL CIRCULATION), and the air returning to the equator at a low level forms the trade winds.

As the air moves from the subtropical highs and into the equatorial trough, its relative VORTICITY causes the air to start turning about vertical axes centered on the subtropical highs, clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. This deflects the wind from a direction at right angles to the equator, producing the northeast and southeast trades.

Where the trades cross the equator, vorticity acts in an opposite sense, and the easterly winds can become westerlies. In summer, for example, when the ITCZ moves to about 5–10°N, trade winds blowing from the southeast in the Indian Ocean south of the equator continue across the equator, where they become southwesterly winds that contribute to the onshore winds which produce the summer MONSOON over southern Asia.

There is some seasonal variation in the strength of the trade winds. They are strongest in winter and weakest in summer. This is because they originate in air flowing outward from the subtropical highs, and these are most intense in winter.

The area affected by the trades also changes with the SEASONS. In March, the northeast trades are found between 3°N and 26°N over the Atlantic and between 5°N and 25°N over the Pacific. In September, they occur between 11°N and 35°N over the Atlantic and between 10°N and 30°N over the Pacific. In March, the southeast trades occur between the equator and 25°S over the Atlantic and between 3°N and 28°S over the Pacific. In September, they are found between 3°N and 25°S over the Atlantic and between 7°N and 20°S over the Pacific.

Weather systems in higher latitudes can also influence the strength of the trades. When these alterations in the distribution of pressure increase the PRESSURE GRADIENT away from the centers of the subtropical highs, the trade winds accelerate in what is called a surge of the trades. They are also affected by the SOUTHERN OSCILLATION. El Niño events (*see* ENSO) cause the trade winds to weaken, fade completely, or even reverse direction. La Niña events cause the winds to strengthen.

Despite these variations, the trade winds are more constant, in both speed and direction, than any other wind system on Earth, and they are especially constant over the ocean. Their constancy was of great importance in the days when goods were traded in sailing ships, and it was noted as soon as vessels were plying regularly through the Tropics.

It is their constancy that gives them their name. In Saxon times, the word *trada* meant footstep or track, and this came into English as *trade,* meaning track. (*Tread* has the same derivation.) Any kind of established track or trail might be called a trade, so a wind that blows almost all of the time and almost always from the same direction was described as a trade wind. The pursuit of a particular occupation was also called a trade, and in time the name came to be attached to the occupation itself.

Once the trade winds had been observed and their reliability verified, scientists began trying to explain them. The first to do so, in 1686, was the British astronomer Edmund Halley (1656–1742). In 1735, the British meteorologist George Hadley (1685–1768) improved on Halley's explanation, but it was not until 1856 that the American meteorologist William Ferrel (1817–91) fully explained the trade winds as part of the general circulation of the atmosphere. (*See* APPENDIX I: BIOGRAPHICAL ENTRIES for information on Ferrel, Hadley, and Halley.)

During the summer, when they extend almost to the tropopause and the westerly winds blowing above them are either nonexistent or too weak to affect the lower troposphere, the trade winds are sometimes called the equatorial easterlies.

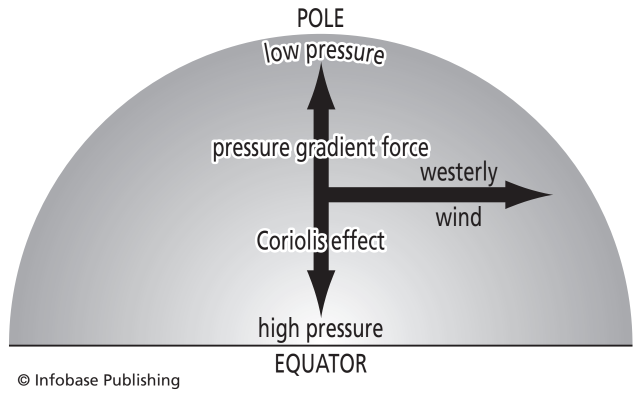
The equatorial westerlies are westerly winds that occur in summer between the northeasterly and southeasterly trade winds. These westerlies are most strongly evident over continents, especially over Africa and southern Asia, where heating of the ground surface produces a pressure distribution that shifts the equatorial trough northward. The westerlies extend to a height of about 1–2 miles (2–3 km) over Africa and 3–4 miles (5–6 km) over the Indian Ocean. They are associated with the summer monsoon over Asia, but their cause is quite different from the pressure pattern that produces the monsoon winds. The equatorial trough does not move far enough from the equator to produce westerly winds over the Pacific or Atlantic Oceans.

The antitrade is a wind that blows at high level in the Tropics as part of the Hadley cell circulation. Its direction is opposite to that of the trade winds, so it blows from the southwest in the Northern Hemisphere and from the northwest in the Southern Hemisphere. Air that has been carried away from the equator by the antitrades subsides over the Tropics to produce the subtropical highs.

A meridional wind is a wind, or component of a wind, that blows parallel to the lines of longitude (meridians). The trade winds have a strong meridional component. Those near the surface blow toward the equator at almost 7 MPH (11 km/h). In the tropical upper troposphere, meridional winds blow away from the equator. These meridional winds comprise the horizontal components of the Hadley cell circulation.

The midlatitude westerlies, or prevailing westerlies, are the prevailing winds of the middle latitudes, between about 30° and 60° in both hemispheres. They affect a region that is bounded on one side by subtropical air and on the other by polar air, and they blow throughout the troposphere, so the upper winds blow in the same direction as the surface winds. The winds blow from the southwest in the Northern Hemisphere and from the northwest in the Southern Hemisphere. Their velocity and frequency are both at a maximum at about latitude 35°–40°. The upper winds are centered on a mean latitude of 45°. There is very little meridional flow, except when the westerly flow is interrupted during the index cycle (*see* ZONAL INDEX). A westerly wave is a wavelike disturbance that is embedded within the prevailing westerlies of middle latitudes.

In the days of sailing ships, brave west winds is the name sailors gave to the strong prevailing westerly winds that blow over the oceans in latitudes 40°N–65°N and 35°S–65°S. The brave west winds are more



Pressure at any height decreases with distance from the equator. This produces a pressure gradient force directed toward the pole. As soon as air moves in response to this force, the Coriolis effect deflects it to the east. When the two forces balance, the resultant wind blows from west to east, producing the prevailing westerlies of middle latitudes.

persistent in the Southern Hemisphere than in the Northern Hemisphere and are strongest in the roaring forties, in latitudes 40–50°S. They are produced by the strong pressure gradient on the side nearest the equator of the frequent DEPRESSIONS that travel from west to east. Consequently, the generally westerly winds fluctuate between northwest and southwest as weather systems pass.

The roaring forties are fierce winds that blow between latitudes 40°S and 50°S. There is no continental land mass in these latitudes to slow the winds over the Southern Ocean. Terrifying though they are to sailors, the roaring forties are not alone. To their south the furious fifties and shrieking sixties blow in latitudes 50°S to 60°S and to the south of 60°S, respectively.

A stratospheric wind is one that blows in the stratosphere. The little that is known about this air movement has been obtained from satellite observations of the way particles are distributed following a major VOLCANIC ERUPTION. There were two significant eruptions in 1991. Mount Pinatubo, located in Mexico at 15.15°N, erupted in June, and Cerro Hudson, in Chile at 45.92°S, erupted in August. Both volcanoes injected ash and SULFUR DIOXIDE into the stratosphere. The cloud from Mount Pinatubo traveled westward, spreading to the north and south as it did so. The cloud from Cerro Hudson traveled eastward and did not widen. This demonstrated that in the Northern Hemisphere low-latitude stratospheric winds blow predominantly from west to east and those in the middle latitudes of the Southern Hemisphere blow from east to west. Very little material from Cerro Hudson reached Antarctica, illustrating the extent to which stratospheric air over the southern polar region is isolated during the late winter (August and September). This isolation from air in lower latitudes prevents air containing OZONE from entering the polar stratosphere and replenishing the depleted OZONE LAYER.

A country breeze is a light, cool wind that blows into a city from the surrounding countryside, especially on calm nights when the sky is clear. It is produced by the urban HEAT ISLAND effect, and the effect is most pronounced on clear calm nights. Warm air rising above the city produces an area in which the AIR PRESSURE is lower than it is in the surrounding countryside. Cool air then flows towards the city center.

A desert wind is one that blows off the DESERT. It is hot in summer, cold in winter, and very dry.

A firn wind, also called a glacier wind, is a KATABATIC WIND that blows from a GLACIER during the day, especially in summer. Air in contact with the glacier is chilled and becomes denser, its increased DENSITY causing it to flow down the slope.

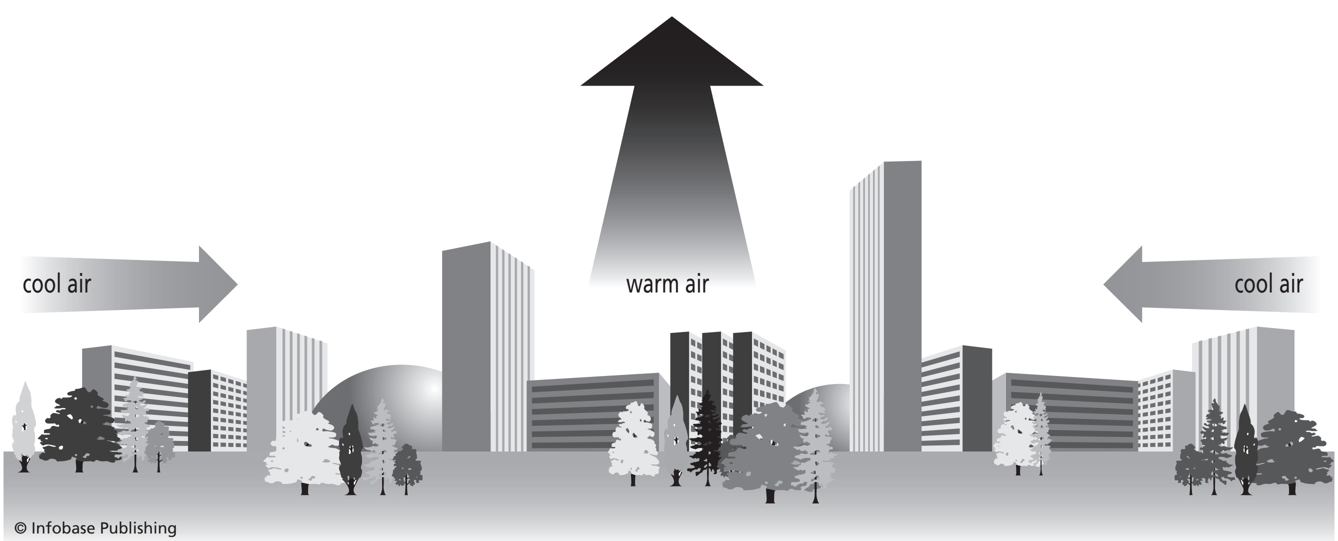
A valley breeze is an ANABATIC WIND that blows during the day in some mountain areas. It most commonly occurs when conditions are calm and the sky is clear, and it is most frequent in summer. As the ground surface warms in the sunshine, air in contact with it is also warmed. This air expands and becomes less dense. Cooler, denser air that is farther from the surface subsides beneath the warm air, pushing the warm air up the mountain sides as a warm breeze. This sometimes causes the development of cumuliform cloud (*see* CLOUD TYPES) above the mountain, leading to SHOWERS or THUNDERSTORMS. Mountainsides where mountain and valley breezes occur regularly are often preferred for growing fruit, because the constant air movement prevents the static conditions in which FROST can form.

A mountain-gap wind, also called a canyon wind, gorge wind, or jet-effect wind, is a local wind that occurs where the prevailing wind is funneled through the space between two mountains and accelerated, so it is markedly faster than most winds in the region where it occurs.

A ravine wind is one that blows along a narrow, mountain valley or ravine. The wind is generated by a pressure gradient between the two ends of the valley. Funneling caused by the constricting effect of the valley sides accelerates the airflow, strengthening the wind.

A stowed wind is a wind that is partly blocked by a physical barrier, such as a range of mountains or hills, so it is forced through gaps between them. This increases the speed of the wind.

A tidal wind is a wind produced by the ATMOSPHERIC TIDES. The term is also applied to a wind that



Warm air rises over the city, producing a region of low pressure near ground level. Cool air blows in from the surrounding countryside as a country breeze.

A valley breeze is a warm wind that blows up the side of a mountain during the day, when air is being warmed by contact with the ground surface and rises up the mountainside.

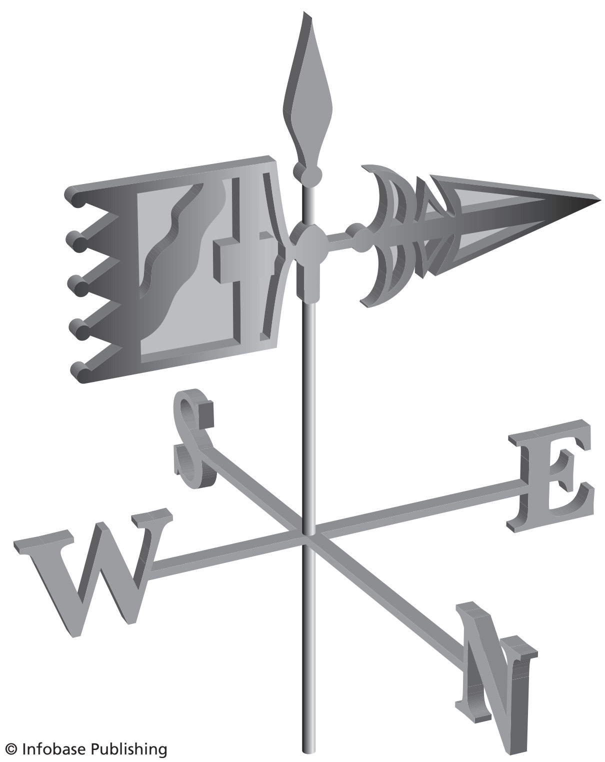
is produced in some tidal inlets by the displacement of air when the TIDE rises strongly. The wind is very light and can be felt only when otherwise the air is calm.

An offshore wind is one that blows across the coast from the land in the direction of the sea. An onshore wind blows across the coast from the sea in the direction of the land.

Perhaps the most famous of all winds, although it occurred only twice, was the kamikaze, the "divine wind" (in Japanese) that saved Japan from invasion in 1274 and again in 1281. The Mongol leader Genghis Khan, who ruled China and Korea, had ordered the Japanese to submit to them. When the Japanese refused, in 1274 a Mongol invasion force of about 40,000 troops sailed in Korean ships for the southernmost Japanese island of Kyushu. Before landing, the invaders had to overcome small Japanese garrisons on the offshore islands of Tsushima and Iki. They did this without difficulty, and advance parties of Mongolian troops landed in several places on Kyushu, but were contained by the Japanese warriors. Had the main Mongol force landed, it is quite possible that it would have overwhelmed the Japanese forces and Japan would have been brought under Mongol rule. Before this could happen, however, a typhoon (*see* TROPICAL CYCLONE) destroyed 200 of the Korean ships and many of the soldiers drowned. The survivors returned to Korea, and the Japanese set about strengthening their defenses. In 1281, the Mongols tried again, this time sending one army of about 40,000 Mongol, Chinese, and Korean troops from Korea and a second army of about 100,000 troops from southern China. The two armies met, but before they could overwhelm the Japanese forces another typhoon struck, sinking almost all of the invading fleet. Of the force of 140,000, it is said that fewer than 28,000 survived. The Japanese believed the typhoon had been sent by the gods to save them from being conquered by foreigners.

wind vane Wind vanes are the most commonly used device for measuring the direction of the wind. The practice of fastening wind vanes to the tops of church steeples and other tall buildings began in Athens in the first century B.C.E., with the TOWER OF THE WINDS.

The wind vane consists of four fixed arms that point to the cardinal points of the compass (north, south, east, and west) and that are labeled N, S, E, and W. Above them is the vane itself, mounted so that it can move freely around a vertical axis. On one side of its axis, the vane has a flat surface that is aligned by the wind. On the other side of the axis, there is a



The traditional wind vane, mounted on top of a church steeple, points into the direction from which the wind is blowing. This one is shaped like an arrow, and many are animal figures.

pointer. The wind pushes the vane to the far side of its axis. Consequently, the pointer indicates the direction from which the wind is blowing. That is why winds are named by the direction from which they blow and not by the direction in which they are blowing. For example, a west (or westerly) wind blows from west to east.

Often the vane is shaped as an arrow, with the flight acting as the vane and the head as the pointer. Other, more fanciful designs are also popular. These are usually figures of animals. Roosters are the favorite, and wind vanes of this design are known as weathercocks, but fish and other birds are also used. They all have a large tail or body to act as the vane and their heads act as the pointers.

Directions that lie between the cardinal points have to be judged by eye. For this reason, and also because a wind vane is mounted so high above the ground, the precise wind direction can be difficult to see clearly.

wine harvest The date when grapes are harvested, the size of the crop, and the quality of the wine that is made from them can be used to infer the weather conditions during the previous year. Wine has always been a product of great commercial importance, and during the Middle Ages many European monasteries relied on it as a source of income. Consequently, harvest records were kept meticulously, and many of them have survived. Crop yields and harvest dates vary according to the variety of grape being grown, but when a grower replaced one variety with another that was also recorded.

Wine harvest records have been used to trace the climatic changes that have taken place since about the year 1000. They show, for example, that prior to 1300, 30–70 percent of wine harvests in southern Germany were described as good, but between 1400 and 1700 the proportion never rose above about 53 percent and sometimes fell to 20 percent. This deterioration coincided with the coldest part of the LITTLE ICE AGE. Similar changes occurred in the French wine-growing regions, and these have also been used in reconstructing the history of climate.

Further Reading

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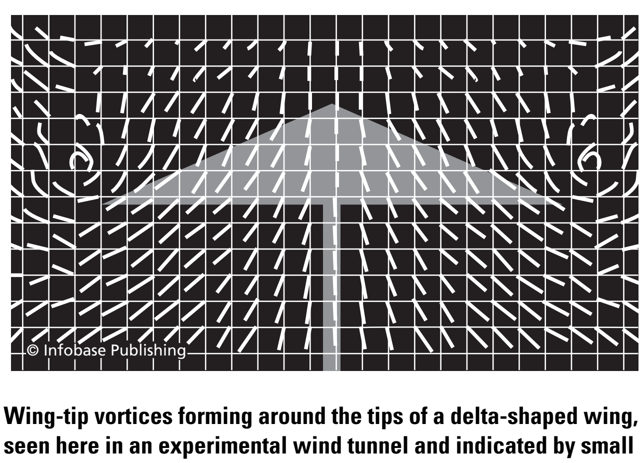
wing-tip vortices Wing-tip vortices are EDDIES that develop around the wing-tips of aircraft and birds and that are sometimes visible as thin streamers of cloud. They result from the way a wing generates lift.

Seen in cross section, the upper surface of a wing is more curved than the lower surface. Air flowing over the wing moves faster over the upper surface than it does over the lower surface because it must cover a greater distance. This reduces the AIR PRESSURE over the upper surface by the BERNOULLI EFFECT, so the pressure is higher on the lower surface than it is on the upper surface. The difference in pressure exerts an upward force on the wing. This is lift, but there is a secondary effect.

Air tends to flow from a region of high pressure to a region of low pressure. The curvature of the upper surface decreases toward the trailing edge (rear) of the wing, so near the trailing edge there is little difference in the curvature of the two surfaces and therefore little difference in the pressure on them. The center of lift, where the maximum lift is exerted, is about one-third of the way back from the leading edge (front) of the wing. Air does not spill around the trailing edge from the high pressure below to the low pressure above, because at the trailing edge there is little difference in the two pressures.

This is not the case at the wing tips, however, because at the tips there is no boundary between the two pressures for the whole cross-sectional distance of the wing. Consequently, air spills over the edge of the wing tip. It then enters the LAMINAR FLOW of air over the main wing surface and is swept to the rear. This



Wing-tip vortices forming around the tips of a delta-shaped wing, seen here in an experimental wind tunnel and indicated by small lengths of wool tied to the intersections of a wire grid

produces an eddy that describes a spiraling path behind the wing tip.

This is the wing-tip VORTEX. Air pressure is a little lower inside the vortex than it is outside. If the air is moist, the lower pressure may be sufficient to cause some WATER VAPOR to condense, producing a streamer of cloud behind the wing tip. This is most often seen behind high-performance aircraft that are turning steeply or pulling out of a dive. It is then that the vortices are strongest and the pressure within them is lowest.

World Climate Program (WCP) The WCP is a program that was established in 1979 by the WORLD METEOROLOGICAL ORGANIZATION to collect and store climate data. The aim of the program is to provide the data necessary for economic and social planning and to improve the understanding of climate processes. Data from the WCP are also used to determine the predictability of climate and to detect climate changes.

The WCP issues warnings to governments of impending climatic changes that may significantly affect their populations. The WCP has four components: the World Climate Data and Monitoring Program, the World Climate Applications and Services Program, the World Climate Impact Assessment and Response Strategies Program, and the World Climate Research Program. The WCP also supports the Global Climate Observing System (GCOS) that covers all aspects of the global climate.

Further Reading

WMO. "World Climate Programme." Available online. URL: www.wmo.ch/index-en.html. Accessed March 7, 2006.

World Meteorological Organization (WMO) The WMO is the United Nations specialized agency that exists to promote the establishment of a worldwide system for gathering and reporting meteorological data, the standardization of the methods used, the development of national meteorological and hydrological services in less-industrialized countries, and the application of meteorological information and understanding to other fields.

The WMO supports and coordinates the work of the national meteorological and hydrological services in its 187 member states. On March 23 each year, the contribution meteorologists and hydrologists make to human welfare and safety is celebrated on World Meteorology Day. Each World Meteorology Day has a theme, and the WMO publishes literature and a film to draw attention to the topic it has chosen for the year. For example, the theme for World Meteorology Day 2006 was "Preventing and Mitigating Natural Disasters."

The WMO was founded in 1947 at the twelfth meeting of its predecessor, the International Meteorological Organization. At their 1947 meeting, the directors of the International Meteorological Organization adopted the World Meteorological Convention, which authorized the creation of the WMO. The convention came into force in 1950, and in 1951 the WMO commenced its operation. Later in 1951, following discussions between the UN and WMO, the WMO became a UN agency.

The first International Meteorological Congress was held in 1874 under the auspices of the International Meteorological Committee, a nongovernmental body consisting of the directors of the national weather services of a number of countries. The committee had been established the previous year with the aim of establishing regular communication among meteorologists throughout the world and developing standards for weather observation and recording. The most important decision made at the congress was to compile and publish an *INTERNATIONAL CLOUD ATLAS*. The name of the committee was later changed to the International Meteorological Organization, and in 1947 it became the World Meteorological Organization (WMO) of the United Nations. The congress, now called the World Meteorological Congress, still meets at intervals of at least four years and sets the policy for the WMO.

The headquarters of the WMO are in Geneva, Switzerland. It has 187 members, 181 of which are member states and six are member territories that maintain their own weather services. The members are arranged as six regional associations, for Africa, Asia, South America, North and Central America, the Southwest Pacific, and Europe. Each association meets once every four years.

WMO policy is set by the World Meteorological Congress, which meets at least once every four years, and policy is implemented by an executive council with 36 members, including the WMO president and two vice presidents. The council meets at least once every year. The WMO also has eight technical commissions that deal with aeronautical meteorology, agricultural meteorology, atmospheric sciences, basic systems, climatology, hydrology, instruments and methods of observation, and marine meteorology. Each commission meets every four years.

The principal activity of the WMO centers on the World Weather Watch. The WMO also maintains the World Climate Program and the Atmospheric Research and Environment Program. The Atmospheric Research and Environment Program coordinates and fosters research into the composition and structure of the atmosphere, the physics and chemistry of clouds, weather modification, tropical meteorology, and weather forecasting. This program also includes the Global Ozone Observing System that was established in the 1950s and now receives data from 140 ground-based stations. The Tropical Cyclone Landfall Program aims to improve understanding of the rainfall and wind field on the coast and farther inland when a tropical cyclone makes landfall.

The international agreement to take steps to halt the depletion of the ozone layer that resulted in the Montreal Protocol on Substances that Deplete the Ozone Layer was based largely on data from the Global Ozone Observing System. The WMO also supports the implementation of the UN Framework Convention on Climate Change, the International Convention to Combat Desertification, and the Vienna Convention on the Protection of the Ozone Layer (*see* Appendix IV: laws, regulations, and international agreements).

Observing stations throughout the world collect meteorological and climatological data, and disseminate them through the WMO communications network. The WMO devised the system of international index numbers for identifying observing stations. Areas of the world are divided into blocks, each of which is given a two-digit number and a further three-digit number identifies each station within each block.

Stations use the international synoptic code to transmit data. Each element of the data is encoded as a series of five-digit numerals. Synoptic code is one of several recognized codes that is used to transmit synoptic weather data and observations. It is used widely throughout the world and is the code officially approved by the WMO. It is one of the codes used by the U.S. National Weather Service (NWS). The NWS also uses the METAR code. The SYNOP code is also used extensively. All of these codes translate observations and data into groups of numbers. This compresses the data and improves the reliability of transmission and reception.

Réseau is the name used by the WMO to describe the global network of weather stations that have been chosen to represent the world climate. The full name is *réseau mondiale,* which is French for "global net work."

Further Reading

WMO. "World Meteorological Organisation." Available online. URL: www.wmo.ch/index-en.html. Accessed March 7, 2006.

World Weather Watch (WWW) World Weather Watch is an international program, run by the World Meteorological Organization, which coordinates the national weather systems of the states that belong to the WMO. The WWW has several components.

The Global Observing System (GOS) gathers data from about 11,000 land-based, surface observing stations, each of which takes readings every three hours and in some cases hourly. There are also approximately 900 upper-air stations collecting data from radiosondes (*see* weather balloon). Approximately 40 percent of the 7,000 vessels belonging to the Voluntary Observing Ship scheme are at sea at any one time, and the GOS receives data from about 900 drifting buoys. About 3,000 aircraft submit data; in 2005, the GOS received almost 300,000 reports from aircraft. The GOS also receives data from five satellites in near-polar orbit and six in geostationary orbit.

The Global Telecommunications System (GTS) links meteorological communications centers throughout the world. The main telecommunication network comprises three world telecommunication centers, in Melbourne, Moscow, and Washington, and 15 regional telecommunication centers. These are in Algiers, Beijing, Bracknell, Brasilia, Buenos Aires, Cairo, Dakar, Jeddah, Nairobi, New Delhi, Offenbach, Toulouse, Prague, Sofia, and Tokyo. The regional centers are at the hub of regional networks for Africa, Asia, South America, North America, Central America and the Caribbean, South-West Pacific, and Europe.

The Global Data-processing and Forecasting Systems (GDPFS) analyze data and prepare forecasts and other information. These are distributed to national meteorological and hydrological services through the GTS.

The Public Weather Services Program (PWSP) forms part of the Applications of Meteorology Program. It strengthens and supports national meteorological and hydrological services in providing reliable weather forecasts.

The WWW also includes the Tropical Cyclone Program, which monitors TROPICAL CYCLONES and alerts national services to their approach, and it supports research into Antarctic meteorology.

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X, Y

xenon Xenon is a rare gas that accounts for about 0.0000086 percent of the atmosphere, or one part in 10 million by volume. It is heavier than the other atmospheric gases. Atomic number 54; atomic weight 131.30; DENSITY (at sea-level pressure and 32°F, 0°C) 0.059 ounces per cubic foot (5.887 grams per liter). Xenon melts at -169.6°F (-111.9°C) and boils at -160.6°F (-107.1°C).

xerophilous Adapted to living in places that have an arid climate.

xerophyte A plant that is adapted to an arid climate.

xerothermic An adjective that is applied to places, climates, or conditions that are hot and dry.

Younger Dryas (Loch Lomond Stadial) The Younger Dryas was a cold, dry period, affecting the whole of the North Atlantic region and with effects that were felt in the TROPICS, where climates became drier, and as far away as New Zealand. It began about 12,900 years ago and lasted for about 1,300 years, ending abruptly 11,640 years ago when the mean temperature increased by about 13°F (7°C) in the space of about 10 years. The Younger Dryas is recognized by soils of that date containing abundant pollen from mountain avens (*Dryas octopetala*), which is an arctic-alpine plant. Its effects have also been detected in ICE CORES from GISP2 (*see* GREENLAND ICE SHEET PROJECT).

When the Younger Dryas began, ICE SHEETS had probably disappeared from the whole of Scotland as the Devensian Glacial drew to a close. By about 10,800 years ago, however, the ice was hundreds of meters thick over the western Highlands of Scotland, and the climate of Europe was similar to that during the glacial. Many scientists believe that the melting of the LAURENTIDE ICE SHEET triggered the rapid onset of the Younger Dryas by releasing large amounts of freshwater that flowed into the North Atlantic. This shut down the GREAT CONVEYOR and produced a SNOWBLITZ effect. There are difficulties with this explanation, however, because there was another, albeit smaller release of freshwater at the end of the Younger Dryas that did not halt the warming. The cause of the dramatic cooling remains uncertain.

Z

zenith angle The zenith angle is the height of the Sun above the horizon. This is measured as the angle between a line linking the observer to the Sun and the vertical (the zenith). The zenith angle (Z) is calculated from:

$$\cos Z = \sin \theta \sin \delta + \cos \theta \cos \delta \cos h$$

where θ is the latitude, δ is the solar DECLINATION, and *h* is the hour angle (this is 0 at noon and increases by 15° (360/24) for each hour either side of noon).

As the zenith angle changes through the day, there is a reversal in the relative intensities of light from directly overhead at two wavelengths (*see* WAVE CHARACTERISTICS). The German word for reversal is *Umkehr,* and this is known as the umkehr effect.

One of the two wavelengths is more strongly absorbed by OZONE than is the other, so a series of measurements of the change in their relative intensities can be used to determine the vertical distribution of ozone.

zonal flow A zonal flow is a movement of air in a generally west-to-east direction, approximately parallel to the lines of latitude. When winds are measured over a large area, they may be separated into their zonal and meridional components (*see* MERIDIONAL FLOW). The average zonal winds, known as the zonal average, are strongest in the upper troposphere (*see* ATMOSPHERIC STRUCTURE) over the subtropics during the three winter months (December, January, and February in the Northern Hemisphere and June, July, and August in the Southern Hemisphere). They are then blowing at an average speed of 89.5 MPH (144 km/h).

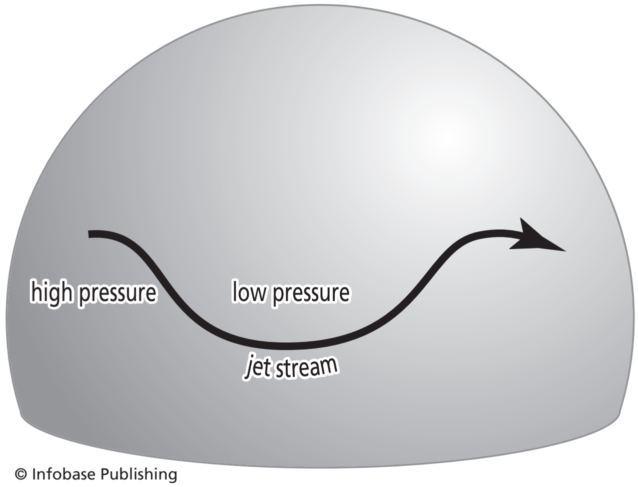
The movement of air in the TROPOSPHERE in a west-to-east direction that is measured over a specified period or with respect to a particular longitude is known as the zonal circulation.

The zonal kinetic energy is the KINETIC ENERGY of the mean zonal wind. It is calculated by averaging the zonal component of the wind along a specified latitude.

A diagram in which the speed of the ZONAL FLOW is plotted against latitude is called a zonal-wind profile (*see* WIND PROFILE).

zonal index The zonal index is a measure of the strength of the westerly winds between latitudes 33° and 55° in both hemispheres, expressed either as the horizontal PRESSURE GRADIENT, or as the corresponding GEOSTROPHIC WIND. A high zonal index indicates strong westerly winds and a continuous, strongly developed, and almost straight JET STREAM. Weather systems move at a fairly steady pace in the same direction as the jet stream. A low index indicates weak westerlies and the formation of a cellular pattern of air flow. The ROSSBY WAVES in the jet stream and polar FRONT are well developed, so the jet stream follows a sinuous path. Low-pressure polar air (*see* AIR MASS) extends far to the south in some places, and in others tropical air extends far to the north.

Progressive changes in the zonal index are cyclical. The full index cycle typically lasts for between three and eight weeks, at the end of which the original circulation



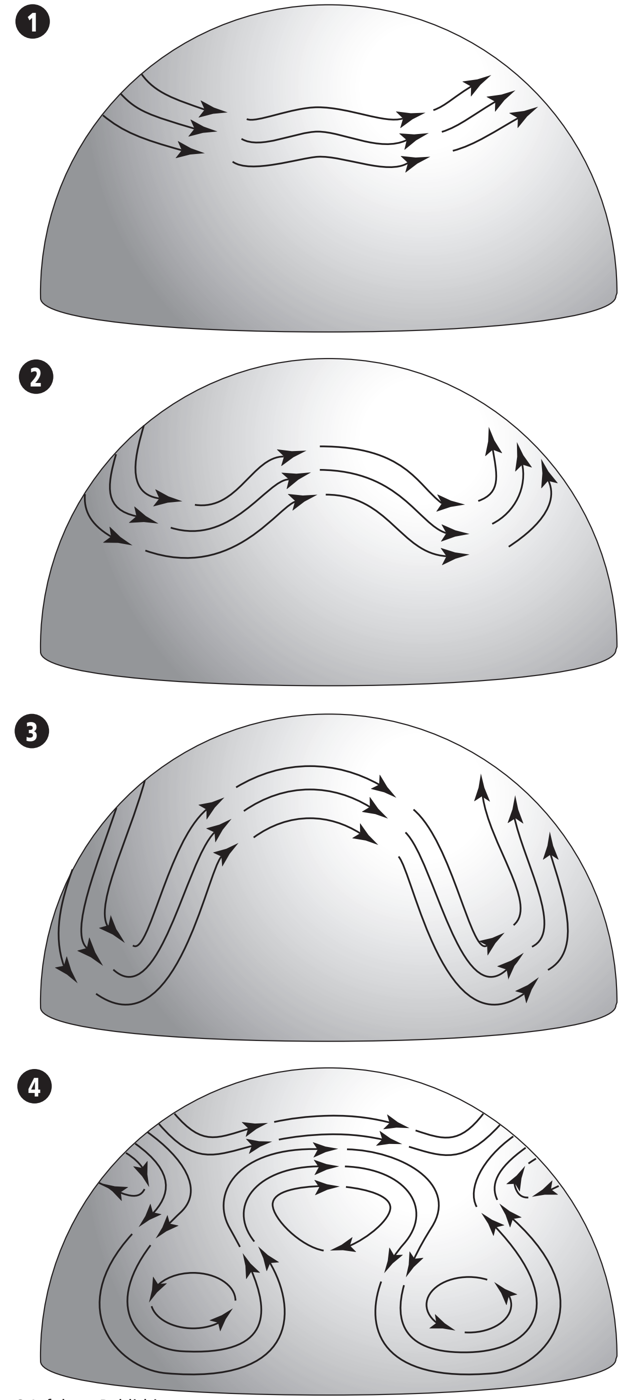
When the zonal index is low, the wave pattern in the jet stream is strongly developed, so the jet stream and polar front follow a very sinuous path.

is restored. The change usually moves westward (from east to west) at a rate of about 60° of longitude a week, but it is very irregular both in the duration of the full cycle and in the speed with which it moves westward. It is especially common in February and March.

The zonal index is a number that represents the difference in AIR PRESSURE between two latitudes, usually 33°N and 55°N. These latitudes mark the boundaries that contain the polar front and polar front jet stream. When the pressure difference is great, the index is said to be high, and when it is small, the index is said to be low.

When the cycle commences, the zonal index is high. The polar front and its jet stream are aligned approximately from west to east, some distance to the north of their mean positions. Polar air lies to the north of the front and tropical air to the south of it, and there is very little mixing between them. A small number of Rossby waves lie along the front and jet stream. The amplitude of the waves is small, and their wavelength is long.

Where the Rossby waves carry the flow northward, that part of the jet stream experiences a stronger CORIOLIS EFFECT (CorF), because the magnitude of CorF increases with latitude. In order to conserve the absolute VORTICITY of the flow, the jet stream develops an equivalent negative vorticity. This turns the jet stream so that it curves cyclonically (*see* CYCLONE). It is then moving back to its original latitude, but it overshoots



Four stages in the development of the index cycle, during which the pressure difference to each side of the polar front weakens: (1) the initial condition, with a high zonal index; (2) the amplitude of the Rossby waves increases and their wavelength decreases; (3) the undulations in the waves become more and more extreme, carrying polar air a long distance south and tropical air a long distance north; (4) the flow breaks down into a series of cells, with anticyclones in the north and cyclones in the south.

and, to compensate, develops positive vorticity that makes it curve anticyclonically (*see* ANTICYCLONE).

This pattern can remain stable for long periods, with low-amplitude, long-wavelength Rossby waves. During an index cycle, however, each overshoot is slightly greater than the one preceding it. Both the cyclonic and anticyclonic curvatures continue for longer, so the wave amplitude increases and the wavelength decreases. The undulations in the jet stream and polar front become more and more extreme. The original zonal (east to west) flow is then much more meridional (north to south and south to north).

Finally, the pattern breaks down altogether. The flow of air joins on either side of the RIDGES and TROUGHS, forming isolated cells. Cells that form from the troughs lie to the south. The flow around them is cyclonic, and they mark areas of low surface pressure. Cells that form from the ridges are located to the north, and the flow around them is anticyclonic. They mark areas of high surface pressure.

At this stage the pattern may temporarily stabilize. This produces BLOCKING, resulting in prolonged periods of weather. On the southern side of the front, at about 33°N (approximately the latitude of Dallas, Texas, and Little Rock, Arkansas), the weather is associated with low pressure. It is associated with high pressure on the northern side, at about 55°N (a little to the north of Edmonton, Alberta, and Belfast, Northern Ireland).

As the anticyclones weaken and the cyclones fill, the cellular pattern dissipates. The original flow then reestablishes itself, with a high zonal index.

Polar outbreaks sometimes occur in North America during the later stages of the index cycle, when the jet stream follows a deeply undulating path. A polar outbreak is an extension of polar air into lower latitudes. A trough in the middle troposphere usually extends over eastern North America in both summer and winter. It is possibly a LEE trough resulting from the effect of the Rocky Mountains on the high-level westerly winds. The flow of air around the trough tends to bring polar air southward, especially when the trough is strong, and the polar air brings cold weather. When the trough is weak the westerly flow of air is stronger and polar outbreaks are less likely.

Appendix I
Biographical Entries

Abbe, Cleveland
(1838–1916)
American
Meteorologist

Cleveland Abbe was the first person to issue regular daily weather bulletins and forecasts. He is sometimes called the "father of the Weather Bureau." He was also influential in the establishment of standardized time zones across the United States.

Born and educated in New York City, Abbe went to study astronomy at the University of Michigan and privately with Benjamin Apthorp Gould (1824–96) at Cambridge, Massachusetts. Abbe taught at the University of Michigan for several years. Afterward, he spent two years, 1864–66, completing his astronomical studies at the Pulkovo Observatory in Russia. When he returned to the United States, he was appointed director of the Cincinnati Observatory.

Like Joseph Henry, Abbe received telegraphic reports of storms and used them to plot their location and timing across the country. These compilations provided him with the information he issued from Cincinnati Observatory in his daily reports called the *Weather Bulletin,* the first of which appeared on September 1, 1869. On September 22 of the same year, he published his first weather forecast.

The government was immediately interested, and on February 2, 1870, Rep. Halbert E. Paine introduced a Joint Congressional Resolution requiring the secretary of war to establish a national meteorological service. President Ulysses S. Grant signed the resolution on February 9, 1870, and the weather bureau began operations in November 1870. It formed part of the recently instituted Division of Telegrams and Reports for the Benefit of Commerce of the Army Signal Service and was headed by an army general. Abbe was appointed his scientific assistant, joined the Signal Service, and started work in 1871, issuing the first of his three-day weather forecasts, based on probabilities, on February 19, 1871. The first "cautionary storm signal" (for the Great Lakes region) was issued on November 8, 1871.

In 1891, the national bureau was renamed the United States Weather Bureau and was transferred from the Army Signal Corps to the Department of Agriculture (it was transferred to the Department of Commerce in 1940). Abbe was the meteorologist in charge and retained this position for the rest of his life. At the same time, he conducted research and taught meteorology at Johns Hopkins University.

His advocacy of standardized time zones culminated in a report on the subject that he wrote in 1879. At that time, each community used its own local time, which was accurate enough but meant travelers had to continually adjust their watches as they moved east or west. The railroad companies had devised their own standardization for the purposes of scheduling services, and these were the basis of the Abbe proposal. The government adopted the idea, and in 1883 the country was divided into four time zones. The same time was used throughout each zone and was based on an average value. This system was later extended to the entire world.

Cleveland Abbe died on October 28, 1916, in Chevy Chase, Maryland, where he and his wife are buried.

Agassiz, Jean Louis Rodolphe
(1807–1873)
Swiss–American
Naturalist

Louis Agassiz was born on May 28, 1807, at Motier, not far from Friborg, on the shore of Lake Morat, in Switzerland, where his father was the Protestant pastor. The family was originally French, but was forced to flee from France after Louis XIV revoked the Edict of Nantes in 1685 and Protestants were no longer tolerated in the country.

Louis's mother, Rose Mayor, taught him to love the natural world. His formal education began with four years at the gymnasium (high school) in Bienne (Biel), northwest of Bern, after which he attended a school in Lausanne. In 1824, he enrolled at the University of Zürich, and in 1826 moved from there to the University of Heidelberg, Germany, but he caught typhoid fever in Heidelberg and had to return to Switzerland to recuperate. In 1827, he enrolled at the University of Munich, Germany. He qualified as a doctor of philosophy (Ph.D.) at the University of Erlangen in 1829 and as a doctor of medicine at Munich in 1830.

Two distinguished naturalists from Munich, J. B. Spix and C. P. J. von Martius, had spent 1819 and 1820 touring Brazil, returning to Germany with a large collection of fishes, most of them from the Amazon River. Spix set about classifying the collection, but in 1826 he died and Martius handed the task over to Agassiz. Agassiz completed the classification, and it was published in 1829, when he was only 22 years old, as *Selecta Genera et Species Piscum* (Selection of fish genera and species). This set the course for his major research.

In November 1831, Agassiz went to Paris, where he continued his studies of fishes, for a short time at the Natural History Museum under the supervision of Georges Cuvier (1769–1832), the eminent comparative anatomist. Cuvier, who had read and been greatly impressed by his work on the Brazilian fishes, befriended the young Agassiz. Alexander von Humboldt also helped him. Following the death of Cuvier in May 1832, Agassiz moved to the University of Neuchâtel, Switzerland, where von Humboldt helped him secure the professorship of natural history. Between 1833 and 1844, Agassiz published *Recherches sur les Poissons Fossiles* (Research on fossil fish) in which he classified more than 1,700 species. He also published major works on fossil echinoderms and mollusks.

In 1836, Agassiz turned his attention to a new question. Boulders that were scattered over the plain of eastern France and in the Jura Mountains were different in composition from the solid rock beneath the ground on which they lay. Some scientists thought these erratics might have been transported to their present positions by GLACIERS. If glaciers can push boulders ahead of them, it means that the glaciers flow, and if flowing glaciers pushed boulders deep into France, it means that at one time the Swiss glaciers must have extended much farther than they do today.

With some friends, Agassiz spent his 1836 and 1837 summer vacations on the Aar Glacier. They built a hut on the ice and called it the "Hôtel des Neuchâtelois." From this base they observed the rocks piled to the sides and at the ends of this and other glaciers and the grooves in the solid rock that looked as though they had been made by scouring as harder stones were dragged past them.

Agassiz continued his investigations, and in 1839 he found a hut that had been built on the ice in 1827 and that had moved a mile (1.6 km) from its original position. He drove a line of stakes into the ice across a glacier and found that by 1841 they had moved and the straight line had changed to a U shape, because the stakes at the center had moved faster than the ones at the sides. By then he was convinced that all of Switzerland had been covered by ice in the geologically recent past. He also concluded that all those parts of Europe where erratic boulders and gravel were found had also lain beneath a great sheet of ice resembling that in Greenland. In 1840, Agassiz published the most important of all his works, *Études sur les Glaciers* (Studies of glaciers).

In 1846, with the help of a grant from King Friedrich Wilhelm IV of Prussia, Agassiz visited the United States, partly to continue his studies but immediately to deliver a series of lectures at the Lowell Institute in Boston. He followed these with other popular and technical lectures in various cities. The lectures were popular, and Agassiz extended his stay, studying North American natural history at the same time. In 1848, he was appointed Professor of Zoology at Harvard University. Agassiz became an American citizen and remained in the United States for the rest of his life, for most of the time at Harvard.

Agassiz found evidence that North America had also been covered by ice, and he traced the shoreline of a vast, vanished lake that had once covered North Dakota, Minnesota, and Manitoba. It is now called Lake Agassiz. Agassiz clearly demonstrated that over Europe and North America there had once been what he called a Great Ice Age.

At Harvard in 1858, Louis Agassiz developed the Museum of Comparative Zoology to assist research and teaching. It was built around Agassiz's own collection, and he was its director from 1859 until his death. His scientific research was of great importance, but he was also one of the finest teachers of science America has ever known. He was devoted to his students and treated them as collaborators. During the second half of the 19th century, every well-known and successful teacher of natural history in the country had at one time been a pupil either of Agassiz himself or of one of his former students.

Despite being one of the most knowledgeable biologists of his time, Agassiz remained steadfastly opposed to the Darwinian concept of evolution by natural selection.

He married twice. Cecile Braun, his first wife, died in 1848 in Baden, a few months after Agassiz had taken up his position at Harvard. In 1850, he married Elizabeth C. Cary, who became his valued scientific assistant.

Louis Agassiz died at Cambridge, Massachusetts, on December 12, 1873. He is buried at Mount Auburn, Cambridge, where his grave is marked by a boulder from the Aar glacial moraine. In 1915, Agassiz was elected to the Hall of Fame for Great Americans.

Further Reading

Academy of Natural Sciences, Philadelphia. "Louis Agassiz (1807–1873)." University of California. Available online. URL: www.ucmp.berkeley.edu/history/agassiz.html. Accessed March 9, 2006.

Aitken, John

(1839–1919)
Scottish
Physicist

John Aitken discovered that the air contains large numbers of very small particles, now known as Aitken nuclei (*see* AEROSOL), and invented the Aitken nuclei counter, an instrument for detecting them. He also discovered the part Aitken nuclei play, as CLOUD CONDENSATION NUCLEI, in the formation of clouds.

John Aitken was born and died at Falkirk, in Stirlingshire. He studied at the University of Glasgow, which awarded him an honorary doctorate in 1889.

Due to poor health, he was never able to hold any official position. Instead, he worked from a laboratory he made at his home. There he constructed his own apparatus and conducted experiments. He described many of his findings in papers published in the journals of the Royal Society of Edinburgh, of which he was a member.

d'Alibard, Thomas-François

(1703–1799)
French
Physicist

Thomas-François d'Alibard performed Benjamin Franklin's famous kite experiment 36 days before Franklin did so.

Franklin had written extensively about electricity, and in 1751 Franklin's friend Peter Collinson (1694–1768), a very distinguished English scientist, assembled his articles and papers on the subject and published them as a short book. Georges-Louis Leclerc, the comte de Buffon (1707–88), obtained a copy of Collinson's book. Buffon was the most eminent French natural scientist of his day—he was made a count (comte) in 1771 and an associate of the French Academy of Sciences and Fellow of the Royal Society of London, both in 1739. Buffon asked d'Alibard to translate the book, which he did.

Other scientists had suggested that clouds might contain electricity and that this was the cause of lightning. Franklin also held this view, and Buffon and d'Alibard devised a way to test it.

They set up their apparatus, which consisted of an iron rod, 40 feet (12 m) long and with a brass tip. They insulated the rod by setting it upon a wooden plank that stood on three wine bottles. On May 10, 1752, a soldier keeping watch on the apparatus heard a clap of thunder. He sent for the village priest. As people from the nearby village stood back, sparks flew from the rod with a crackling sound. The priest wrote to tell d'Alibard what had occurred, and on May 13 d'Alibard submitted a report to the Academy of Sciences. In his report, d'Alibard said: "In following the path that Mr. Franklin has traced for us, I have obtained complete satisfaction." The experiment was repeated in Paris on May 18 and the king of France sent his congratulations to Franklin through Collinson.

When Franklin performed his kite experiment on June 15, he was unaware that d'Alibard had already done so.

Amontons, Guillaume
(1663–1705)
French
Physicist

Guillaume Amontons, one of the most ingenious inventors of his age, was born in Paris on August 31, 1663. His father was a lawyer, originally from Normandy. Guillaume studied the physical sciences, celestial mechanics, and mathematics, as well as drawing, surveying, and architecture, but so far as is known he did not attend a university. He earned his living as a government employee, working on a range of public works.

While still in his teens, Amontons became profoundly deaf. Far from regarding this as a handicap, he considered it a blessing, because it allowed him to concentrate on his scientific work without distraction.

In 1687, he invented a new type of hygroscopic HYGROMETER, based on the expansion and contraction of a substance as it absorbs and loses atmospheric moisture (the modern hair hygrometer was invented in 1783 by Horace de Saussure). The following year he devised an optical telegraph (*see* TELEGRAPHY), which he thought would be of help to deaf people. Messages were transmitted by means of a bright light that was visible to a person with a telescope at the next station. He demonstrated it to the king some time between 1688 and 1695, but it was never adopted.

In 1695, Amontons invented a BAROMETER that did not require a reservoir of mercury. This meant it could be used at sea, where mercury barometers gave unreliable readings because the level of the mercury in the reservoir oscillated with the motion of the ship.

The same year he improved on the air thermoscope (*see* THERMOMETER) that had been invented by Galileo in 1593. Galileo's design used the expansion and contraction of the air in a tube to alter the level of water. The disadvantage of this was that the volume of the water was also affected by changes in AIR PRESSURE. Galileo was unaware of the effect of air pressure, but Amontons knew how to remove it. Instead of water he used mercury, then adjusted the height of the mercury until the air filled a fixed volume. After that, changing the temperature of the air in the tube altered the pressure it exerted on the mercury, and it was this changing pressure that the instrument measured. The Amontons thermometer was more accurate than Galileo's, and he was able to use it to show that, within the limits of his instrument, water always boiled at the same temperature, but it was not accurate enough for most scientific uses.

No one had yet devised a scale by which temperature could be measured. This lack prevented him from discovering Charles's law (*see* GAS LAWS), but his new thermometer allowed him to take the study of gases a step further than Mariotte had done. He noticed that for a particular change in temperature, the volume occupied by a gas always changes by the same amount. This led to Amonton's law, which he described in 1699 and which can be stated as $P_1T_2 = P_2T_1$, where P_1 is the initial pressure, P_2 is the altered pressure, T_1 is the initial temperature, and T_2 is the altered temperature. It also allowed Amontons to visualize a temperature at which gases contracted to a volume beyond which they could contract no further. This was the concept of absolute zero (*see* TEMPERATURE SCALES).

Amontons also invented a type of clock called a clepsydra, operated by the flow of water. He proposed that his clepsydra could be used at sea, although it would not have been accurate enough to measure longitude.

In 1690, Amontons became a member of the French Academy of Sciences. He published a number of papers and one book, *Remarques et expériences physiques sur la construction d'une nouvelle clepsydre, sur les baromètres, thermomètres, et hygromètres* (Observations and physical experiences on the construction of a new clepsydra, on barometers, thermometers and hygrometers), which appeared in 1695.

Amontons died in Paris on October 11, 1705.

Aristotle
(384–322 B.C.E.)
Greek
Philosopher

Aristotle was born in 384 B.C.E. at Stagirus, a Greek colony on the coast of Macedonia. Both his parents were Greek. His father, Nichomachus, was the personal physician to the king of Macedonia, Amyntas III, but Nichomachus died when Aristotle was still a boy. Aristotle was then brought up by a guardian, Proxenus, and in about 367 B.C.E., when he was 17, Proxenus sent him to the Academy in Athens that was led by the philosopher Plato (428 or 427–348 or 347 B.C.E.). Aristotle remained at the Academy for 20 years, first as a pupil and then as a teacher.

In 347 B.C.E., Athens was at war with Macedonia. Amyntas had died and the new king was his son, Philip II. Then Plato died. Perhaps for political reasons, because he was sympathetic to the Macedonian cause, or perhaps because of the change in the leadership of the Academy, Aristotle left Athens. He settled first on the coast of Anatolia, in what is now Turkey, then on the island of Lesbos, where he lived from 345 B.C.E. to 343 B.C.E. Finally, he returned to Macedonia. In the course of his travels he married Pythias, the daughter or niece of Hermias, the ruler of the land where Aristotle first arrived after leaving Athens.

Back in Macedonia, Philip appointed Aristotle to supervise the education of his son, a 13-year-old boy called Alexander, who later became known as Alexander the Great. Later in his life Aristotle was very wealthy, possibly from the money he was paid for teaching Alexander.

Aristotle returned to Athens in about 335 B.C.E., and for the next 12 years he taught at the Lyceum, one of the three most famous schools in the city, established in the grounds of the temple to Apollo Lyceius, hence the name. There Aristotle began to assemble a library of books and maps and a museum of natural history. He also established a zoo with animals that were captured during Alexander's campaigns in Asia.

Alexander died in 323 B.C.E., and the opponents of the Macedonians became powerful in Athens. Aristotle was associated with a renowned Macedonian general, and he was charged with impiety. Rather than face trial, and possibly death, he moved to Chalcis (now called Khalkis) on the Greek island of Euboea, north of Athens. The following year he fell ill and died. He was 62 years old.

Aristotle was one of the most original thinkers who ever lived. Every subject interested him. He wrote about logic, ethics, politics, biology, physics, astronomy, and many other topics. His writings are contained in 47 surviving works. Some of these comprise several volumes and others are very short.

One of his works is called *Meteorologica*. The title means "account (*logos*) of lofty things (*meteoros*)" and from it we derive our word *METEOROLOGY*.

In *Meteorologica,* Aristotle set out his own explanations for the weather. He had studied Egyptian ideas on the subject and the methods for classifying winds that had been devised by the Babylonians, and in addition to these he drew on a wide variety of sources.

He maintained that the weather is confined to the region between the Earth and the Moon. This region is composed of four elements: earth, air, fire, and water. Earth and water are heavy and sink, while air and fire are light and rise. Aristotle proposed theories to explain the formation of clouds, rain, hail, wind, thunder, lightning, and storms. He argued, for example, that some of the WATER VAPOR formed during the day does not rise very high because the ratio of the fire that is raising it to the water being raised is too small. At night the water cools and descends and is then called DEW, or hoar FROST if it freezes before it has condensed to water. It is dew, he said, when the vapor has condensed to water and the heat is not so great as to dry up the moisture that has been raised, nor the cold sufficient for the water to freeze. Aristotle observed that although hailstones are made from ice, hailstorms are most common in spring and autumn. They are rare in winter and happen when the weather is mild. He suggested that in warm weather the cold forms discrete areas within the surrounding heat and this could cause water vapor to condense rapidly. That is why RAINDROPS are bigger in warm weather than they are when it is cold. If the cold is very concentrated, however, it can freeze the raindrops as they form, producing hail.

Aristotle had no instruments to measure TEMPERATURE, AIR PRESSURE, or HUMIDITY. Nor did he have the facilities to compile a picture of weather conditions over a large area. Lacking any means to validate his ideas, Aristotle was not in a position to develop an accurate understanding of atmospheric processes. The importance of his contribution to scientific thinking arises from his insistence on basing theories on observed facts rather than tradition or unsupported opinion.

Arrhenius, Svante August
(1859–1927)
Swedish
Physical chemist

Svante Arrhenius was born on February 19, 1859, on the estate of Vik, near Uppsala, Sweden, that was owned by the University of Uppsala. In 1860, the family moved to Uppsala.

Svante began his education at the cathedral school in Uppsala. He was brilliantly clever, especially at mathematics, and was accepted as a student at Uppsala

University when he was only 17. He studied chemistry, physics, and mathematics, graduating in 1878, and then stayed on to start working for his doctorate. After a time he grew dissatisfied with the quality of the teaching in physics, and in 1881 he moved to Stockholm to study under the physicist Erik Edlund (1819–1888).

Arrhenius completed his doctoral thesis in 1884 and submitted it to Uppsala University. He wrote it in French: *Recherches sur la conductibilité galvanique des électrolytes* (Investigations on the galvanic conductivity of electrolytes). An electrolyte is a solution of a chemical in water that conducts electricity. The first part of his thesis dealt with ways to measure the electrical conductivity of very weak solutions and the second with the reason the solution is conductive. This, he proposed, is because the dissolved substance dissociates into charged IONS (for example, common salt, which is sodium chloride (NaCl) dissociates into sodium (Na^+) and chloride (Cl^-) ions) and the ions move through the solution.

Arrhenius presented his thesis to his professor, a man he greatly admired. According to his own account, Arrhenius said: "I have a new theory of electrical conductivity as a cause of chemical reactions." The professor replied "This is very interesting. Good bye." The professor knew that many theories are formed and almost all of them turn out to be wrong and soon disappear. He concluded, therefore, that Arrhenius's theory was most probably mistaken. Like most of his colleagues, the professor believed in experimentation, and Arrhenius had performed no experiments in the course of developing his idea. The thesis was accepted, but it was awarded only fourth class, the lowest grade. The thesis later earned Arrhenius a Nobel Prize.

Undeterred by the lack of interest at Uppsala, Arrhenius sent copies of his thesis to several of the most eminent chemists of the time. This led to the offer of a job at the University of Riga, Latvia, and the offer persuaded the Uppsala authorities to reconsider their opinion. Toward the end of 1884, he was offered a post at Uppsala, and later a traveling fellowship that allowed him to meet other scientists working in the same field.

In 1891, Arrhenius was offered a professorship at the University of Giessen, Germany, but declined it, because he preferred to remain in Sweden. Instead, he accepted a lectureship at the Stockholms Högskola (High School), where in 1895 he became professor of physics. From 1897 until 1905, Arrhenius was also rector. The high school was equivalent to the science faculty of a university, but it was not empowered to award degrees or accept doctoral theses. It became the University of Stockholm in 1960.

Arrhenius retired from the professorship in 1905 and refused another invitation from Germany, this time to become a professor at the University of Berlin. In 1905, the Swedish Academy of Sciences decided to establish a Nobel Institute for Physical Chemistry and Arrhenius was appointed director. He remained in this position until shortly before his death.

Arrhenius was a man of wide interests. He applied his knowledge of chemical reactions to the effects on the body of toxins and antitoxins, describing this in a series of lectures he delivered in 1904 at the University of California. He was interested in immunology, and on the origin of life on Earth. Arrhenius was the first scientist is propose the idea of panspermia, according to which life arrived on Earth in the form of spores that had drifted through space. This idea was out of favor for many years, but recent discoveries of extremophiles—single-celled organisms that flourish in extreme environments—and of bacteria that have survived prolonged periods in space have revived interest in it. He wrote about astronomy, especially comets and the possibility of life on Mars.

He also studied what is now called the GREENHOUSE EFFECT. In 1896, he published a paper, "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground" (*Philosophical Magazine,* vol. 41, pages 237–271). He was not the first scientist to consider the absorption of energy by CARBON DIOXIDE, and it was the French mathematical physicist Jean-Baptiste-Joseph Fourier (1768–1830) who suggested in 1827 that the atmosphere acts like the glass of a greenhouse, allowing light in but preventing heat from leaving. Arrhenius turned earlier speculations into hard numbers.

He calculated the effect carbon dioxide would have if the atmospheric concentration of it were altered. He worked out the resulting change in mean temperature for 13 belts of latitude, each of 10 degrees from 70°N to 60°S, for the four seasons of the year, and the mean for the year. For each of these belts of latitude and seasons, and for the whole year, he worked out what the temperature would be if the carbon dioxide concentration were 67 percent, 150 percent, 200 percent, 250 percent, and 300 percent of the concentration that actually existed in the late 19th century. He calculated that a doubling of atmospheric carbon dioxide would increase the mean annual temperature by 8.91°F (4.95°C) at the equator and by 10.89°F (6.05°C) at 60°N. The task involved thousands upon thousands of calculations, all of which he performed by paper and pencil.

Arrhenius received the 1903 Nobel Prize in chemistry for his work on electrolytes. He also received many other awards and honorary degrees. He married twice, first in 1894 to Sofia Rudbeck, by whom he had a son, and in 1905 to Maria Johansson, by whom he had one son and two daughters.

Arrhenius was a happy, contented, genial man who made many friends and delighted in meeting them. During World War I, he worked successfully to obtain the release of German and Austrian scientists who were prisoners of war.

He was also a popular lecturer and author. In his later years he was in constant demand and traveled widely to attend meetings and deliver lectures. His incessant hard work may have weakened his health, because he was only 68 when he died in Stockholm on October 2, 1927. He is buried in Uppsala.

Further Reading

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Beaufort, Francis

(1774–1857)
Irish
Meteorologist, hydrographer, and naval officer

Francis Beaufort is the scientist who devised the scale of wind force that bears his name (*see* Beaufort wind scale). He was born in Navan, County Meath, Ireland, where his father, the Reverend Daniel Augustus Beaufort, was the rector. The family was of Huguenot origin. Francis's father was keenly interested in geography and topography—the art of drawing the natural and built features of a town or area of countryside—and from an early age Francis came to share his enthusiasm.

In 1789, Francis joined the East India Company, the trading company that had been established to administer British commercial interests in India, but eventually came virtually to govern that country. Francis stayed with the company for only a year before leaving to join the Royal Navy, with which he was to spend the rest of his working life. He was 16 years old and began as a cabin boy, but by the age of 22 he had risen to the rank of lieutenant and was serving on HMS *Phaeton*. In 1805, he was given his first command, of HMS *Woolwich*.

Within a very short time of going to sea, Francis recognized the importance of weather conditions and the value of recording them. He began to keep a journal, a habit he maintained for the rest of his life.

By the time of his first command he had become a hydrographer—a scientist who studies, describes, and charts river courses, coastlines, and the depth of the sea—and his task with the *Woolwich* was to survey the Río de la Plata region, in South America. In 1829, he was made the official hydrographer for the Admiralty. He carried out extensive surveying, for example around the Turkish coast in 1812, and was influential in sending out several important voyages of discovery. He also kept up his great interest in meteorology, especially those aspects that affected the operation of sailing ships at sea.

In 1806, Commander Beaufort, as he was then, drew up the chart of wind forces for which he is famous, his *Wind Force Scale and Weather Notation*. Its aim was to provide guidance for sailors, telling them how much sail they should set on a full-rigged warship according to the wind, and in its first version it included no information about the actual speed of the wind. These were not added until long after Beaufort had died. His original scale classified winds from force 0 to force 12—this being a wind "that no canvas could withstand."

In June 1812, during his surveying work in the eastern Mediterranean on HMS *Frederiksteen,* Beaufort led the rescue of some of his men who had been attacked by forces commanded by the local rulers. Beaufort was seriously wounded in the encounter and spent a long time convalescing in Portugal. At the end of the year he was ordered back to Britain. He never went to sea again.

Robert FitzRoy, captain of the *Beagle* on which Charles Darwin sailed, used the Beaufort scale and spoke highly of it, and in 1838 it was introduced throughout the Navy. Captains were required to include details of the wind in their daily logs. In 1874, modified to include details of the state of the sea and the visible effects of the wind on land, the scale was adopted by the International Meteorological Committee for use in international meteorological telegraphy.

Beaufort was knighted for his service in 1848, and by the time he retired in 1855, he had reached the rank of rear admiral. Admiral Sir Francis Beaufort had served in the Royal Navy for 68 years. He died two years later.

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Beckman, Ernst Otto

(1853–1923)
German
Chemist

Ernst Beckman, inventor of the Beckman THERMOMETER, was born at Solingen, to the southeast of Düsseldorf, on July 4, 1853. He worked as a pharmacist's assistant before enrolling at the University of Leipzig to study chemistry and pharmacy.

After graduating, Beckman taught at the Technische Hochschule (technical high school) in Brunswick. Later he became professor of physical chemistry at the Universities of Leipzig, Giessen, and Erlangen. He was appointed director of the Laboratory for Physical Chemistry and Electrochemistry at Leipzig, and in 1912 he became the first director of the newly established Kaiser Wilhelm Institute for Physical Chemistry and Electrochemistry in Berlin.

Ernst Beckman died in Berlin on July 13, 1923.

Beer, August

(1825–1863)
German
Mathematician, chemist, and physicist

August Beer was the author of BEER'S LAW and he contributed to LAMBERT'S LAW, which is sometimes known as the Beer–Lambert law.

August Beer was born on July 31, 1825, in Trier. He went to school in Trier, and after leaving school in 1845 he went to Bonn University to study mathematics and natural science, where he worked as an assistant and collaborator to the mathematician and physicist Julius Plücker (1801–1868). Beer was awarded his doctorate in 1848 and was promoted to the faculty of philosophy. In 1850, he began teaching at the university.

Beer conducted research into optics and theories of light. His book *Einleitung in die höhere Optik* (Introduction to higher optics) was published in 1854. Translated into many languages, it became the standard work on theories of light. In 1856, Beer became professor of mathematics at Bonn University.

August Beer died in Bonn on November 18, 1863. At the time he was working on a textbook in which he aimed to bring together the whole of mathematical physics. The book was published posthumously in two volumes in 1865 and 1869.

Bentley, Wilson Alwyn

(1865–1931)
American
Photographer of snowflakes

For 50 years, Wilson A. Bentley studied and then photographed SNOWFLAKES. Eventually, he accumulated an archive of more than 5,000 images and became widely known as "the Snowflake Man."

Bentley was born on February 9, 1865, at the family farm in the village of Jericho, Vermont. His mother had been a schoolteacher prior to her marriage, and she taught Wilson at home until he was 14. She used a small microscope as a teaching aid, and Wilson became fascinated by the world it revealed to him. In particular, he studied the shapes of snowflakes, dewdrops (*see* DEW), FROST, and hailstones (*see* HAIL). He recorded these by drawing what he saw, but this proved unsatisfactory and eventually he acquired the bellows camera and microscope objective that allowed him to photograph them. All of his photomicrographs were taken with this original camera.

Snowflakes consist of ICE CRYSTALS. These have a variety of shapes and can be arranged in an almost infinite number of ways, so that each snowflake is unique. What Bentley discovered, however, is that the temperature and pattern of air circulation within a cloud could be deduced from the form of the ice crystals that fell from it.

Each summer, Bentley turned his attention to the study of rain. He devised a method for measuring the size of RAINDROPS by exposing a dish containing a layer of sifted flour, about 1 inch (2.5 cm) thick. Raindrops formed the flour into little balls of dough. When these were dried, they were approximately the same size as the drops that caused them. The method is still used. From the size of the raindrops he deduced how they had formed. Between 1898 and 1904, he made more than 300 measurements of raindrops.

In 1898, Bentley published his first magazine article, in *Popular Scientific Monthly.* After that he wrote many popular articles and scientific papers, describing many of his most original ideas in the *Monthly Weather Review. Snow Crystals,* his only book, was published in 1931 in collaboration with William J. Humphreys, the chief physicist at the UNITED STATES WEATHER BUREAU, who persuaded him to do it. Writing the book involved sifting through his collection of photomicrographs and selecting nearly 2,500 of his favorites. *Snow Crystals* by Wilson A. Bentley and William J. Humphreys (published by McGraw-Hill and republished in 1962 by Dover) contains about 10 pages of text and more than 200 pages of Bentley's illustrations.

In 1924, Bentley received the first research grant ever to be awarded by the American Meteorological Society. The amount was small, but it was a deserved recognition by the scientific community for the work Bentley had been doing for 40 years.

Despite his interest in the weather, Wilson Bentley remained a farmer. After the death of his father, Wilson and his brother worked the farm between them, and Bentley contributed his full share of the physical work. They succeeded and the farm prospered.

Bentley kept detailed meteorological records throughout most of his life, the last on December 7, 1931. Soon after that he fell ill and died at the farm from pneumonia on December 23, 1931.

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Bergeron, Tor Harold Percival

(1891–1977)
Swedish
Meteorologist

Tor Bergeron was born on August 15, 1891, at Godstone, near London, England. He was educated at the universities of Stockholm, Sweden, and Leipzig, Germany, and in 1928 he obtained his Ph.D. from the University of Oslo, Norway.

As part of his education, Bergeron spent the three years from 1918 until 1921 as a student and collaborator of Vilhelm Bjerknes, the Norwegian meteorologist who in 1917 had established what became the most important meteorological research institute in the world, at the Bergen Geophysical Institute. After he qualified, Bergeron joined the staff at the institute.

In 1935, Bergeron proposed a mechanism for the formation of RAINDROPS in cold clouds (*see* CLOUD TYPES). He calculated that ICE CRYSTALS would grow by gathering water at the expense of supercooled water droplets (*see* SUPERCOOLING). This is called the Bergeron process. The crystals would form SNOWFLAKES, and as the snowflakes fell from the base of the cloud into warmer air they would melt and reach the surface as water droplets. This mechanism was later confirmed experimentally by the German meteorologist Walter Findeisen, and it is now known as the Bergeron-Findeisen mechanism (*see* RAINDROPS).

From 1935 until 1945, Bergeron taught at the University of Stockholm, and in 1946 he moved to the University of Uppsala, in Sweden. He was professor of METEOROLOGY at the University of Uppsala from 1947 until 1961.

Bergeron died in Stockholm on June 13, 1977.

Bernoulli, Daniel

(1700–1782)
Swiss
Natural philosopher

Daniel Bernoulli was born at Groningen, the Netherlands, on February 9, 1700. His father, Johann (sometimes called Jean) Bernoulli (1667–1748) was trained as a physician, but worked as a mathematician. Daniel had an older brother, Nikolaus (1695–1726), who studied law and by the age of 27 was professor of law at the University of Bern, Switzerland, but mathematics was his real passion.

At the time of Daniel's birth, Johann was a professor at the University of Groningen. Johann's elder brother Jakob (sometimes called Jacques) Bernoulli (1654–1705) was also a distinguished mathematician and experimental physicist. Since 1687, he had been professor of mathematics at the University of Basel, Switzerland. After Jakob's death in 1705, Johann succeeded him at Basel and so, at the age of five, Daniel moved to Switzerland. His younger brother Johann (1710–90) was born in Basel and he, too, was a mathematician. In 1743, Johann succeeded his father as professor of mathematics at Basel.

Daniel was educated in Basel. He enrolled at the University of Basel when he was 13 and specialized in philosophy and logic, passing his baccalaureate examination (equivalent to graduating from high school) at the age of 15. When he was 16, he obtained his master's degree. His father wanted him to become a merchant, but commerce did not appeal to Daniel and he refused. He wanted to be a mathematician like the other members of his family, but his father insisted there was no money to be made in that profession. Eventually, they compromised, and in 1717 Daniel began to study medicine at Basel. During his studies he also spent some time at the universities of Heidelberg in 1718 and Strasbourg in 1719, returning to Basel in 1720. The thesis for which he was awarded his doctorate in 1721 was on the action of the lungs.

Having qualified as a doctor and satisfied his father, Daniel sought an academic position, but without success, and he moved to Venice to continue studying medicine. He intended to move to a famous medical school at Padua, but illness kept him in Venice, where he concentrated on mathematics. In 1724, he published a book called *Exercitationes Mathematicae* (Mathematical exercises). He also designed an hourglass that could be used on ships, even in heavy seas. He submitted this to the French Academy of Sciences, and when he returned to Basel in 1725 he learned that it had won a prize.

Daniel also learned that his book had attracted wide attention, and he was offered a professorship in mathematics at the Russian Academy in St. Petersburg. His brother Nikolaus was also offered a professorship in mathematics there, so in 1725 the two men traveled to Russia together. In less than a year Nikolaus died from a fever. This greatly saddened Daniel, and he did not like the Russian climate. Johann, his younger brother, joined him in 1731. Daniel was applying for posts at Basel, and in 1733 he became professor of anatomy and botany. He and Johann left Russia together, visited Danzig (now Gdansk), Hamburg, the Netherlands, and Paris, and finally reached Basel in 1734. In 1750, Daniel became professor of natural philosophy at Basel, and he retained this post until he retired in 1777. The chair at St. Petersburg was later occupied by Daniel's pupil and nephew Jakob Bernoulli (1759–89).

The prize Daniel won for his hourglass was the first of 10 prizes he received from the French Academy for work on astronomy, magnetism, and a variety of nautical topics. He also wrote on political economy and probability.

Daniel published his most important work, *Hydrodynamica* (Hydrodynamics) in 1738. In it he discussed the theoretical and practical aspects of pressure, velocity, and equilibrium in fluids and showed the link between the pressure of a fluid and its velocity. This is a consequence of the conservation of energy, although more than a century was to pass before that concept was formulated clearly (*see* THERMODYNAMICS, LAWS OF). The relationship between pressure and velocity is now known as the Bernoulli principle, and its consequences as the BERNOULLI EFFECT.

In *Hydrodynamica* Bernoulli also assumed that gases are composed of minute particles. This allowed him to produce an equation of state (*see* GAS LAWS) and to relate atmospheric pressure to altitude.

Daniel Bernoulli was predominantly a mathematician and a friend of many of the most eminent mathematicians of his day. The Swiss mathematician Leonard Euler (1707–83) traveled to St. Petersburg to work with him in 1727, and the French mathematician Jean le Rond d'Alembert (1717–83) was also a close friend.

Bernoulli received many honors and was elected to most of the scientific academies of Europe. He died in Basel on March 17, 1782.

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Bjerknes, Jacob Aall Bonnevie

(1897–1975)
Norwegian-American
Meteorologist

The son of Vilhelm Bjerknes, Jacob was born in Stockholm, and during World War I he helped his father organize the network of WEATHER STATIONS that supplied them with the data they used to develop their theories of AIR MASSES and polar FRONTS. Jacob also discovered that DEPRESSIONS originate as waves on fronts.

In 1939, Jacob moved to the United States, and in 1940 he became professor of METEOROLOGY at the University of California, Los Angeles. He became a United States citizen in 1946.

After World War II, Bjerknes conducted extensive studies of the upper atmosphere and JET STREAM, in 1952 being among the first to use photographs taken by high-altitude research rockets for this purpose. Bjerknes also studied the climatic consequences of the interaction of the ocean and atmosphere in the tropical Pacific and was the first to propose, in 1969, what became known as the Bjerknes hypothesis. This holds that ENSO arises from changes in sea-surface temperature, leading to changes in wind strength and direction, leading to changes in the ocean circulation, leading to further changes in sea-surface temperature. Bjerknes died in Los Angeles.

Bjerknes, Vilhelm Friman Koren
(1862–1951)
Norwegian
Physicist and meteorologist

Vilhelm Bjerknes was one of the founders of modern METEOROLOGY and scientific WEATHER FORECASTING. He was born in Oslo. His father, Carl Anton Bjerknes (1825–1903), was professor of mathematics at Christiania (now Oslo) University, and Vilhelm helped him with some of his experiments in hydrodynamics before leaving to spend 1890 and 1891 in Germany working as an assistant to and collaborator with the physicist Heinrich Hertz (1857–94). Bjerknes then spent two years as a lecturer at the School of Engineering (Högskola) in Stockholm and in 1895 was appointed professor of applied mechanics and mathematical physics at the University of Stockholm.

In 1897, Bjerknes developed a synthesis of hydrodynamics and thermodynamics that allowed him to propose a system for forecasting weather scientifically. In 1904, he published a scientific paper outlining a method of numerical forecasting. The Carnegie Institution supported this work, allowing Bjerknes to employ a long series of "Carnegie assistants" who joined the "schools" he founded first at Leipzig and later at Bergen.

Bjerknes returned to Norway in 1907 as a professor at Kristiania (the spelling had been changed) University and, in 1910 and 1911, he and three of his assistants (the Swedish meteorologist Johan W. Sandström and the Norwegians Olaf D. Devik and T. Hesselberg) published *Dynamic Meteorology and Hydrography.* This book described their research thus far and proposed many new techniques for weather forecasting as well as suggesting improvements to existing ones. In 1912, Bjerknes was appointed professor of geophysics at the University of Leipzig. While there, he founded the Leipzig Geophysical Institute, his first school.

In 1917, during World War I, Bjerknes returned to Norway to found his second school, the Bergen Geophysical Institute, as part of the Bergen museum. It is now part of the University of Bergen. He joined the staff of the University of Oslo in 1926 and remained there until his retirement in 1932.

Bjerknes did his most important work while at the Bergen Institute. During World War I, he and his colleagues established a network of WEATHER STATIONS throughout Norway. These reported observations and measurements to Bergen, where they were assembled to produce general pictures of weather conditions at particular times over a wide area. Studying these pictures led Bjerknes and other members of the Bergen School to conclude that there exist AIR MASSES that differ from one another and that these masses are separated by distinct boundaries. Likening the masses to opposing armies, they called the boundaries between them fronts and developed a frontal theory to account for their development, disappearance, and the weather associated with them.

The Bergen frontal theory also explained the way CYCLONES form over the Atlantic. Bjerknes described this work in 1921 in a book that became a classic: *On the Dynamics of the Circular Vortex with Applications to the Atmosphere and to Atmospheric Vortex and Wave Motion.* This formed the basis for the modern theory and practice of meteorology.

Vilhelm Bjerknes was an inspired and popular teacher who attracted talented workers and made sure they received full recognition for their work.

Vilhelm Bjerknes died in Oslo on April 9, 1951.

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Black, Joseph

(1728–1799)
Scottish
Chemist

Joseph Black discovered the ways in which CARBON DIOXIDE can be released into the air naturally and therefore that this gas is a normal constituent of the air. He also discovered LATENT HEAT.

Black was born in Bordeaux, France, on April 16, 1728. His father was a wine merchant and the family was of Scottish descent, although his father was born in Belfast, Ireland. In 1740, Joseph was sent to Belfast to be educated, and from there he went to Glasgow University, where he studied medicine and natural sciences. His courses included chemistry, for which he displayed aptitude and enthusiasm, becoming more like an assistant to his teacher William Cullen (1712–90) than his student. He moved to Edinburgh University in 1751 to complete his medical studies, and in 1754 he submitted a thesis for his doctor's degree.

The thesis described his researches into the effect of heating magnesia alba (magnesium carbonate, $MgCO_3$). Black found that heating this compound released a gas, which he detected by weighing, that was distinct from the ordinary air. In fact, this gas had been described more than a century earlier by Jan van Helmont (1577–1644), but Black pursued his investigation further and published a fuller account of it in 1756, with the title *Experiments Upon Magnesia Alba, Quicklime, and Some Other Alcaline Substances*. His work showed that what he called "mild alkalis" (carbonates) are causticized (made more alkaline) when they lose this gas and that they become less causticized when they absorb it. This demonstrated that the gas is acid.

Calcium carbonate ($CaCO_3$) was one of the "other alcaline substances" Black studied. He found that when this is heated the same gas is released and the solid substance is converted to quicklime, or calcium oxide (CaO), but that the quicklime can also recombine with the gas. Because it can be "fixed" by being absorbed into a solid substance Black called the gas "fixed air." This is the gas we now know as carbon dioxide, and the reaction he described would now be written as:

$$CaCO_3 \leftrightarrow CaO + CO_2$$

Black used a balance to measure the change when $MgCO_3$ is heated, and he also measured the loss in weight when $CaCO_3$ loses CO_2. He measured how much $CaCO_3$ was needed to neutralize a measured amount of acid. This attention to measurement was new to chemistry, and its importance was recognized some years later in the work of Antoine Lavoisier (1743–94). Investigating the properties of "fixed air," Black discovered that a candle would be extinguished if it was placed in an airtight container. He knew that heat released carbon dioxide, so suspected that this is what was extinguishing the flame, but when he added a substance that would absorb the gas the candle still would not burn. He passed on this problem to one of his students, Daniel Rutherford (1749–1819), who discovered the gas that extinguished the flame is what he called "phlogisticated air," which we know as NITROGEN.

In 1756, the year his book was published, Black returned to Glasgow to succeed William Cullen as lecturer in chemistry, and he was also appointed professor of anatomy at Edinburgh University, although he exchanged the post for that of professor of medicine. Joseph Black was a practicing physician.

Around 1760, Black was becoming interested in a different problem. He found, by careful measurement, that when ice is warmed it melts slowly, but its temperature does not change. This led him to suppose that the intensity of heat is not the same thing as the quantity of heat, and that THERMOMETERS measure only heat intensity. As the ice melted, he concluded it was absorbing a quantity of heat that must have combined with the particles of ice and become latent in its substance. *Latent* means "hidden." He called this latent heat, and at the end of 1761 he verified its existence experimentally. Black introduced the topic of latent heat into his lectures, and he described his work on it to a literary society in Glasgow in April 1762.

In 1764, Black and his assistant William Irvine (1743–97) measured the even larger amount of latent heat that is involved when water boils and WATER VAPOR condenses, although their measurements were not very accurate. Black never published any account of his work on latent heat, with the result that others were able to claim the credit. Jean-André Deluc (1727–1817) also discovered latent heat, independently and at about the same time as Black.

Much of Black's research involved heating substances. In the course of it he noticed that equal masses of different substances require different amounts of heat to raise their temperatures to the same degree. This led to the concept of specific heat (*see* HEAT CAPACITY).

In 1766, Black again succeeded his old teacher and friend William Cullen, this time to become professor of chemistry at Edinburgh University. Joseph Black died in Edinburgh on November 10, 1799. He published very little during his lifetime, but after his death his friend John Robison (1739–1805) published his lecture notes, with some additions from his pupils, together with a biographical preface by his friend. This appeared in 1803 as *Lectures on the Elements of Chemistry, Delivered in the University of Edinburgh*.

Boltzmann, Ludwig

(1844–1906)
Austrian
Theoretical physicist

Ludwig Boltzmann made important contributions to the kinetic theory of gases (*see* KINETIC ENERGY) and thermodynamics (*see* THERMODYNAMICS, LAWS OF). Josef Stefan (1835–93) had observed experimentally that when a substance is heated the radiation it emits increases as the fourth power of the temperature. Boltzmann developed a mathematical explanation for this phenomenon, and it is now known as the STEFAN-BOLTZMANN LAW.

Ludwig Boltzmann was born in Vienna on February 20, 1844. He was educated in Vienna and in Linz and studied at the University of Vienna, where Josef Stefan was one of his teachers. Boltzmann received his Ph.D. from that university in 1866.

In 1867, Boltzmann became an assistant at the Physics Institute (Physikalisches Institut) in Vienna. He then held a series of professorships. He was professor of theoretical physics at the University of Graz (1869–73) and professor of mathematics at the University of Vienna (1873–76). He then held a series of professorships in theoretical physics at the universities of Munich (1889–93), Vienna (1894–1900), where he succeeded Stefan, Leipzig (1900–02), and Vienna (1902–06). In 1904, Boltzmann visited the United States, calling at Stanford University and the University of California at Berkeley, and he lectured at the World's Fair in St. Louis.

Boltzmann showed that the second law of thermodynamics is essentially statistical. A system will approach a state of thermodynamic equilibrium because this is overwhelmingly the most probable state in which to find it. His explanation was based on the idea that matter is composed of atoms. This idea was strongly resisted by certain other physicists who held that the behavior of matter should be described only in terms of energy. A heated debate ensued between the "atomists" led by Boltzmann and the "energists" led by Wilhelm Ostwald (1853–1932).

Boltzmann became depressed by the way other physicists had attacked his work and failed to understand it. On September 6, 1906, he took his own life at Duino, near Trieste—now in Italy but at that time in Austria.

In 1828, the Scottish botanist Robert Brown (1773–1858) had described the erratic movements of pollen grains in water, and in a paper published in 1905 Albert Einstein (1879–1955) showed that this Brownian motion could be explained if the pollen grains were being struck by moving molecules of water. This established that matter is made from atoms and their behavior should be understood statistically. Boltzmann was vindicated, but the news did not reach him in time to prevent his tragic death.

Bouguer, Pierre

(1698–1758)
French
Physicist and mathematician

Pierre Bouguer studied the intensity of sunlight and the effect on it of its passage through the atmosphere.

He was born at Croisic, Britanny, on February 16, 1698. His father was a hydrographer and taught Pierre about the geography of fresh and salt water. Pierre was a prodigy and began teaching hydrography at Le Havre when he was only 15 years old. Bouguer also compiled tables of atmospheric REFRACTION and invented the heliometer, an instrument used to measure the diameter of the Sun and the angular distance between stars. Pierre Bouguer became professor of hydrography at Croisic and, in 1730, at Le Havre.

Pierre Bouguer died in Paris on August 15, 1758.

Boyle, Robert

(1627–1691)
Irish
Natural philosopher

Robert Boyle was an aristocrat. His father, Richard Boyle, was the earl of Cork, and Robert was his seventh

Robert Boyle (1627–1691), the natural philosopher. ***(Hulton Archive/Getty Images)***

son and 14th child. He was born on January 25, 1627, at Lismore Castle, in Ireland. He learned to speak Latin and French while still a small child, and he was sent to Eton College, near London, at the age of eight. After three years at Eton, in 1638 he traveled abroad with a French tutor. In 1641, he arrived in Italy and spent the winter in Florence studying the work of Galileo.

Boyle returned to England in 1644 and immediately devoted himself to a life of scientific inquiry. Drawn to others who shared his interests, it was not long before Boyle joined a group of people who called themselves the "Invisible College." They held frequent meetings at Gresham College, in London, and some of the members also met in Oxford. Boyle moved to Oxford in 1654, and there he carried out his most important scientific work.

In 1657, Boyle read of an air pump that had been invented by the German physicist Otto von Guericke (1602–86). The pump was meant to evacuate the air from a chamber, and Boyle enlisted the help of Robert Hooke (1635–1703) to improve it. Boyle and Hooke became lifelong friends. By 1659, the pump was finished and Boyle began using it to experiment on the properties of air. He published the results of this work in 1660 with the title *New Experiments Physico-Mechanical Touching the Spring of Air and its Effects.* Boyle had discovered that the volume occupied by a gas is inversely proportional to the pressure under which the gas is held. This relationship is known in English-speaking countries as Boyle's law (*see* GAS LAWS). He also found that the weight of a body varies according to the amount of BUOYANCY supplied by the atmosphere.

Boyle and Hooke also studied combustion. They found that neither charcoal nor sulfur will burn when air is excluded, no matter how strongly the vessel containing them is heated, but they will burst into flames as soon as air is allowed into the container. When either charcoal or sulfur is mixed with potassium nitrate (saltpetre), however, the mixture will burn in a vacuum. Boyle concluded from this that both potassium nitrate and air contain some ingredient that is necessary for combustion. Boyle did not identify that ingredient, however. Joseph Priestley (1733–1804) isolated it in 1774, and in 1777 Antoine-Laurent Lavoisier (1743–94) gave it the name oxygen.

In 1661, Boyle published another book, *The Sceptical Chymist,* in which he advanced the idea that matter is composed of "corpuscles." These are of various shapes and sizes, and they are able to combine into groups. Each group of corpuscles makes up a chemical substance. Boyle was the first scientist to use the word *analysis* to describe the separation of a substance into its constituents. He invented a hydrometer for measuring the DENSITY of liquids and made the first match by coating a rough paper with phosphorus and placing a drop of sulfur on the tip of a small stick. The stick ignited when it was drawn along a crease in the paper. He made a portable camera obscura that could be extended or shortened like a telescope in order to focus an image on a piece of paper stretched across the back of the box, opposite the lens.

By a charter granted by King Charles II and passed on August 13, 1662, the Invisible College became the "Royal Society, for the improvement of naturall knowledge by Experiment." The charter named Boyle as a member of the council. Boyle was elected president of the society in 1680, but declined because he was unwilling to take the necessary oath.

In addition to his scientific work, Boyle was deeply interested in theology. He learned Hebrew, Greek, and Syriac in order to be able to read scriptural texts in their original languages. His will provided for the founding of a series of lectures aimed at proving the Christian religion against the views of other religions, but with the proviso that disputes between Christians should not be mentioned.

In 1668, Boyle returned to live in London with his sister. He remained in London for the rest of his life. Boyle died there on December 30, 1691.

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(1862–1927)
German
Geographer and glaciologist

Eduard Brückner was born at Jena, in Saxony, Germany, on July 29, 1862, the son of Alexander Brückner, a teacher of Russian history, and Lucie Schiele. He was educated at the gymnasium (high school) in Karlsruhe, and from 1881 until 1885 he studied physics and METEOROLOGY at the University of Dorpat (now Tartu, Estonia). He then continued his studies in Dresden and Munich.

In 1885, Brückner joined the staff of the Deutsche Seewarte in Hamburg. Established in 1876, the Seewarte supplied weather information for ships using the port of Hamburg. It developed into the modern German weather service. From 1888 until 1904, he was a professor at the University of Bern, Switzerland, and from 1899 to 1900 he was rector of the university. He married Ernestine Stein in 1888. In 1904, he returned to Germany to become a professor at the University of Halle, and in 1906 was appointed a professor at the University of Vienna, Austria, a post he held until his death.

Brückner was an authority on alpine GLACIERS, and he was especially interested in the effect of glaciers on surface features of the landscape. He was convinced that climate change is of great importance, with direct economic and social implications. He conducted extensive research and made many theoretical studies of changes that have occurred in the past. In the course of these he discovered the 35-year cycle that now bears his name (*see* BRÜCKNER CYCLE). His interest in the subject is indicated by the titles of some of the papers he published. These include "How Constant is Today's Climate?" (1889), "Climate Change since 1700" (1890, and the paper in which his cycle was first mentioned), "Influence of Climate Variability on Harvest and Grain Prices in Europe" (1895), "An Inquiry About the 35 Year Periods of Climatic Variations" (1902), and "Climate Variability and Mass Migration" (1912).

Brückner died in Vienna on May 20, 1927.

Buchan, Alexander

(1829–1907)
Scottish
Meteorologist

The man who is acknowledged to have been the most eminent British meteorologist of the 19th century was born at Kinnesswood, Kinross, Scotland, on April 11, 1829. He became a schoolteacher, teaching all subjects. His favorite leisure pursuit was botany.

Following a public meeting held in Edinburgh on July 11, 1855, a society was formed with the aim of establishing WEATHER STATIONS throughout Scotland. The society became the Scottish Meteorological Society, and it operated the weather stations from 1856 until 1920, when that task was taken over by the METEOROLOGICAL OFFICE. In December 1860, Buchan was appointed secretary to the society, and he remained in the post until his death in 1907.

Buchan also edited the *Journal of the Scottish Meteorological Society* from its first issue in 1864, and he wrote a great deal of its material. During his editorship, the journal published Thomas Stevenson's description of his louvered screen (*see* STEVENSON SCREEN). The screen is still widely used.

In 1883, the Scottish Meteorological Society opened a meteorological observatory on Ben Nevis, the highest mountain in Britain. Buchan was closely involved with the establishment of the observatory and with the running of it. The observatory remained in operation until 1904.

Buchan established his reputation in 1867, with the publication of his *Handy Book of Meteorology.* This became a standard textbook and remained in use for many years. In 1869, he wrote a paper, "The Mean Pressure of the Atmosphere and the Prevailing Winds

Over the Globe," for the Royal Society of Edinburgh. He also wrote papers on the circulation of the atmosphere and on ocean circulation. It was also in 1869 that he published his paper on "Interruptions in the Regular Rise and Fall of Temperature in the Course of the Year" in the *Journal,* describing what came to be called BUCHAN SPELLS.

Buchan was made a member of the Meteorological Council in 1887 and was elected a fellow of the Royal Society in 1898. In 1902, he was the first person to be awarded the Symons Medal, the greatest honor meteorologists can bestow on one of their colleagues.

Alexander Buchan died in Edinburgh on May 13, 1907.

Budyko, Mikhail Ivanovich

(b. 1920)
Belorussian
Physicist and meteorologist

Budyko was the first scientist to calculate the balance of heat received from the Sun and radiated from the Earth's surface, checking his calculations against observational data from all parts of the world. In 1956, he published his results in his book *Heat Balance of the Earth's Surface.* This work changed CLIMATOLOGY from being a qualitative discipline, based on measuring climatic data from all over the world, into a more physical discipline. Professor Budyko became a pioneer of physical climatology, adding to his 1956 book an atlas, completed in 1963, that shows the Earth as viewed from space with all aspects of the Earth's heat balance displayed. Calculations of climate change are based on this atlas.

By 1960, Professor Budyko was already concerned about the possibility of a general rise in world temperatures caused by human activity. He suggested the day might come when it became necessary to scatter particles in the stratosphere (*see* ATMOSPHERIC STRUCTURE) in order to reflect solar radiation and reduce the rate of temperature increase. In 1972, he was able to confirm a link between past climate changes and changes in the atmospheric concentration of CARBON DIOXIDE. Budyko warned then that his analysis indicated a general warming of the world's climates due to the rise in the carbon dioxide concentration brought about by the increasing consumption of fossil fuels. His 1972 calculations predicted a rise in TEMPERATURE of about 6.3°F (3.5°C) from this cause between 1950 and about 2070.

Budyko's studies of the effects on climate of altering the composition of the atmosphere led him in the early 1980s to ponder the climatic consequences of a large-scale thermonuclear war. He suggested that such a war might inject such a huge quantity of AEROSOLS into the atmosphere that the entire world would be plunged into deep cold, a NUCLEAR WINTER that might threaten human survival.

Mikhail Budyko was born on January 20, 1920, at Gomel, Belarus. He was educated in Leningrad, and from 1942 until 1975 he worked at the Main Geophysical Observatory, Leningrad (St. Petersburg), where he was the director from 1972 to 1975. He was then appointed to his present position, as head of the Division for Climate Change Research, at the State Hydrological Institute, St. Petersburg, the position he still holds. He was elected an Academician of the Russian Academy of Sciences in 1992.

He has been awarded many prizes, including the Lenin National Prize (1958), Gold Medal of the World Meteorological Organization (1987), A. A. Grigoryev Prize of the Russian Academy of Sciences (1995), and the Blue Planet Prize (1999) for his contribution to environmental research.

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Buys Ballot, Christoph Hendrick Diderik

(1817–1890)
Dutch
Meteorologist

Christoph Buys Ballot was born at Kloetinge, Zeeland, the Netherlands, on October 10, 1817. In 1847, he was appointed professor of mathematics at the University of Utrecht, and in 1854 helped to found and was the first director of the Royal Netherlands Meteorological Institute. He remained in this post until his death.

In 1857, Buys Ballot described the wind circulation around areas of low and high atmospheric pressure. He based his description on his studies of meteorological records, and it quickly became known as a law attributed to him. Buys Ballot did not know that the American meteorologist William Ferrel (1817–91) had reached the same conclusion on theoretical grounds some months earlier. When he learned of this, Buys Ballot acknowledged Ferrel's prior claim to the discovery, but it was too late, and what should be known as Ferrel's law is usually called BUYS BALLOT'S LAW.

Buys Ballot died on February 3, 1890.

Cavendish, Henry

(1731–1810)
English
Physicist

Henry Cavendish discovered that the composition of air is the same everywhere and at all times. Cavendish was born at Nice, France, on October 31, 1731. He was of aristocratic descent. His paternal grandfather was the duke of Devonshire, and his maternal grandfather was the duke of Kent. Henry Cavendish was extremely wealthy, but he was reclusive and made no use of the large fortune he inherited.

Cavendish was educated at Dr. Newcome's Academy in Hackney, London, and in 1749 he went to Peterhouse College of the University of Cambridge. He left Cambridge in 1753 without taking a degree. This was not unusual at the time. His father encouraged his scientific interests and introduced him to the Royal Society. Cavendish became a fellow of the Royal Society in 1760.

Henry Cavendish studied "fixed air" (CARBON DIOXIDE), and in his first paper, published in 1776, he proved the existence of "inflammable air" (HYDROGEN). He also studied what he called "common air," and in 1783, after collecting air samples on 60 days and performing 400 analyses of them, he found that air always has the same composition. He also discovered that a small portion of the air is inert. This was later found to consist mainly of ARGON. Cavendish also studied heat and discovered LATENT HEAT and specific heat before Joseph Black (1728–99), but did not publish his findings.

In the course of his studies of electricity, Cavendish oxidized NITROGEN by sending electric sparks through the air. When he dissolved the resulting gas in water and analyzed it, he found it to be nitric acid (HNO_3). Cavendish also determined the freezing point of mercury.

Henry Cavendish died in Clapham, London, on February 24, 1810.

Celsius, Anders

(1701–1744)
Swedish
Astronomer and physicist

Anders Celsius was born in Uppsala, Sweden, on November 27, 1701. Nils Celsius, his father, was professor of astronomy at the University of Uppsala, and both of Anders' grandfathers were also professors at Uppsala: Magnus Celsius (his paternal grandfather) was professor of mathematics, Anders Spole (his maternal grandfather) preceded Nils as professor of astronomy. Several of his uncles were also scientists.

Anders was educated in Uppsala, and in 1730 he was appointed to succeed his father as professor of astronomy. There was no major observatory in Sweden at that time, so soon after his appointment Celsius embarked on a tour of the major European observatories. His tour lasted five years and in the course of it he met many of the leading astronomers of the day. Between 1716 and 1732, Celsius and his companions made 316 observations of the aurora borealis (*see* OPTICAL PHENOMENA). He published these in Nuremburg in 1733. Celsius and Olof Hiorter, his assistant, discovered that the aurorae are magnetic phenomena.

While visiting Paris in 1734, Celsius met the French astronomer Pierre-Louis Maupertuis (1698–1759), who invited him to join an expedition to Torneå, in Lapland (today on the border between Sweden and Finland, but then in northern Sweden). The purpose of the expedition was to measure the length of one degree of latitude along a meridian (degree of longitude) close to the North Pole and to compare their result with a similar measurement taken in Peru (in a region that is now in Ecuador). The Lapland expedition took place in 1736–37, and it confirmed the opinion of Isaac Newton (1642–1727) that the Earth is flattened at the poles.

His participation in this expedition made Celsius famous in his own country, and he was able to persuade the Swedish government to finance the building at Uppsala of an observatory equipped with instruments Celsius had bought during his European tour. The Celsius Observatory opened in 1741, with Celsius as its first director. Celsius made some of the earliest attempts to measure the magnitude of stars.

In the 18th century, astronomy was not studied purely to obtain information about the stars and planets. Governments were busy delineating the borders of their territories, and to do this accurately their surveyors needed astronomical data to fix positions—inaccurate maps could and did lead to war. Accordingly, Celsius conducted many measurements that were used in the Swedish General Map. He may also have been the first person to observe that the Scandinavian landmass is slowly rising. We now know that this is due to the release of pressure following the melting of the FENNOSCANDIAN ICE SHEET (*see* GLACIOISOSTASY), but Celsius thought the sea level was falling because the sea was evaporating.

In 1742, Celsius presented a paper to the Royal Swedish Academy of Sciences in which he proposed that all scientific measurements of TEMPERATURE should be made on a scale based on two fixed points that occur naturally. This led to the development of the temperature scale that bears his name (*see* TEMPERATURE SCALES).

Celsius published most of his scientific papers through the Royal Swedish Academy of Sciences, and he was its secretary from 1725 until 1744. He strongly favored the introduction of the Gregorian calendar. This had been tried in 1700 by omitting the leap days between 1700 and 1740, but 1704 and 1708 were declared leap years by mistake, and in 1712 Sweden returned to the Julian calendar. Celsius and his supporters eventually succeeded, and the new calendar was introduced in 1753 and all 11 supernumerary days were dropped together.

By then Celsius was dead. He died from tuberculosis in Uppsala on April 25, 1744.

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Charles, Jacques-Alexandre-César

(1746–1823)
French
Physicist and mathematician

The discoverer of Charles's law was born at Beaugency, Loiret, on November 12, 1746. He worked as a clerk in the Ministry of Finance in Paris, and while there he became interested in science. Having heard about the experiments Benjamin Franklin (1706–90) had conducted with electricity, Charles gave popular public lectures in which he popularized Franklin's discoveries, demonstrating them with apparatus he constructed himself.

In June 1783, the Montgolfier brothers made their first experiments with unmanned hot-air balloons at Annonay, in the south of France. When news of this reached Paris, the Academy of Sciences asked Jacques Charles to study the invention. He realized that HYDROGEN would be a much better lifting gas than hot air. With the help of two friends, Nicolas and Anne-Jean Robert, he successfully launched a hydrogen balloon in August 1783. On December 1, Charles and Nicolas Robert became the first people to ascend in a balloon. In later flights Charles reached a height of nearly 10,000 feet (3,000 m). This made him a popular hero, and the king, Louis XVI, invited him to move his laboratory to the Louvre.

Charles made his most important discovery in about 1787. As long ago as 1699 Guillaume Amontons (1663–1705) had published his finding that different gases expand by the same amount for a given rise in TEMPERATURE. Using OXYGEN, NITROGEN, and hydrogen, Charles repeated the experiments by which Amontons had reached this conclusion and was able to calculate the precise amount by which the gases expanded. He found that for every 1.8°F (1°C) rise in temperature their volume increased by 1/273 of the volume they had at 32°F (0°C). This meant that if the gas could be cooled to -459.4°F (-273°C) its volume would be zero. This came to be known as absolute zero (*see* UNITS OF MEASUREMENT).

Charles did not publish the results of these experiments, but he did inform Joseph Gay-Lussac (1778–1850) about them. Gay-Lussac repeated them, and the resulting general rule came to be known in France as Gay-Lussac's law but outside France it is called Charles's law (*see* GAS LAWS).

In 1785, Charles was elected to the Academy of Sciences. Later he became professor of physics at the Paris Conservatoire des Arts et Métiers. He died in Paris on April 7, 1823.

Clapeyron, Benoit-Paul-Emile

(1799–1864)
French
Mathematician and engineer

In 1834, Emile Clapeyron published a paper explaining the ideas of the French engineer Sadi Carnot

(1796–1832). Carnot had shown that the amount of work a heat engine can do depends entirely on the difference in TEMPERATURE of the working fluid entering the engine and the hot exhaust gases. He also showed that energy can change its form, but it can be neither created nor destroyed. Until Clapeyron's paper, however, few people knew of Carnot's work. Once Clapeyron had explained it, the significance of Carnot's discovery became apparent. William Thomson (Lord Kelvin, 1824–1907) and Rudolf Clausius (1822–88) developed it into the second law of thermodynamics (*see* THERMODYNAMICS, LAWS OF). Clapeyron also studied the relationship between temperature and SATURATION VAPOR PRESSURE. The Clausius–Clapeyron equation describes the heat of vaporization of a liquid.

Emile Clapeyron was born in Paris on February 26, 1799. He was educated at the École Polytechnique, from which he graduated in 1818, and then at the École des Mines, where he studied engineering.

In 1820, Clapeyron and his friend Gabriel Lamé (1795–1870) went to Russia to lead and train a team of engineers that had been recruited to improve the condition of the country's bridges and roads. Clapeyron taught mathematics at the School of Public Works in St. Petersburg for 10 years. He returned to France in 1830 and became a professor at the École des Mineurs in St. Étienne. Clapeyron and Lamé had proposed building a railroad between Paris and St. Germain. In 1835, the project was approved, and they were asked to head the project, but Lamé had been offered the chair in physics at the École Polytechnique and left to take up the appointment, leaving Clapeyron in charge of the railroad.

Clapeyron became a professor at the École des Ponts et Chaussées in 1844, and in 1848 he was elected to the Paris Academy of Sciences.

He died in Paris on January 28, 1864.

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Clarke, Arthur Charles

(b. 1917)
English
Science fiction writer and physicist

Arthur C. Clarke was the first person to suggest that satellites might be used for communications and that they might be placed in geostationary ORBITS—sometimes called Clarke orbits. Clarke was born at Minehead, Somerset, on December 16, 1917. During World War II, he served in the Royal Air Force, where he worked on the experimental trials of ground-controlled approach (GCA). That was the first use of RADAR to allow aircraft to land safely in poor visibility.

After the war Clarke enrolled at King's College, London, from where he graduated in physics and mathematics in 1948. He had already published, in 1945, the technical paper in which he outlined the principles of geostationary orbits and the use of satellites in communications. In 1954, in a letter to Harry Wexler, head of the Scientific Services Division of the UNITED STATES WEATHER BUREAU, Clarke suggested using orbiting satellites to obtain data for use in WEATHER FORECASTING.

Arthur C. Clarke has received many awards and honors. These include the 1982 Marconi International Fellowship, the gold medal of the Franklin Institute, the Lindbergh Award, the Vikram Sarabhai Professorship of the Physical Research Laboratory, Ahmedabad, and a fellowship of King's College, London. He received a knighthood on May 16, 2000.

Since 1956, Sir Arthur has lived in Colombo, Sri Lanka.

Clausius, Rudolf Julius Emmanuel

(1822–1888)
German
Theoretical physicist

Clausius was one of the founders of the study of thermodynamics and the principal originator of its second law (*see* THERMODYNAMICS, LAWS OF). He coined the word *entropy.*

Rudolf Clausius was born on January 2, 1822, in Köstin, Pomerania (now Koszalin, Poland). His education began at the local school run by his father and continued at the Gymnasium (high school) in Stettin. He enrolled at the University of Berlin in 1840 and obtained his doctorate in 1848 from the University of Halle.

After obtaining his doctorate, Clausius taught in Berlin at the Royal Artillery and Engineering School and in 1855 moved to Switzerland, to become professor of physics at Zurich Polytechnic. He returned to Germany in 1867 to take up an appointment of professor of physics at the University of Würzburg, and in 1869 moved to the University of Bonn as professor of physics.

In 1870, during the Franco–Prussian war, Clausius organized a volunteer ambulance service operated by his students. Wounds received in the war left him in perpetual pain.

Clausius died in Bonn on August 24, 1888.

Coriolis, Gaspard-Gustave de

(1792–1843)
French
Physicist, mathematician, and engineer

The scientist who was the first person to explain why moving bodies, such as winds and ocean currents, are deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere was born in Paris on May 21, 1792. His family came from Provence, in the south of France. They were lawyers and were made aristocrats (hence the "de" in the family name) in the 17th century. The French Revolution stripped them of their privileges and wealth, and Gaspard's father became an industrialist, living in the town of Nancy.

In 1808, Gaspard de Coriolis commenced his studies at the École Polytechnique, the school that trained government officials. He completed them at the École des Ponts et Chaussées (School of Bridges and Highways). In the course of his studies there he spent several years in the Vosges Mountains on active service with the corps of engineers.

De Coriolis graduated in highway engineering and was determined to become an engineer, but his health was poor and his father's death left him with the responsibility of keeping the family. In 1816, he joined the staff of the École Polytechnique, first as a tutor and then as an assistant professor of analysis and mechanics. In 1829, he took up a position as professor of mechanics at the École Centrale des Arts et Manufactures, where he remained until 1836, when he became professor of mechanics at the École des Ponts et Chaussées. In 1838, he was made director of studies at the École Polytechnique. He was elected a member of the mechanics section of the French Academy of Sciences in 1836.

De Coriolis was a highly talented scientist, but suffered from poor health, which prevented him from realizing his full potential. Nevertheless, he made several important contributions to science. He succeeded in establishing the term *work* as a technical term, defining it as the displacement of a force through a distance. In dynamics he introduced a quantity, $\frac{1}{2} mv^2$, for which he coined the term *force vive,* now called kinetic energy.

In 1835, he made the contribution to physics for which he is still remembered, describing it in a paper called "Sur les équations du mouvement relatif des systèmes de corps" (On the equations of relative motion of a system of bodies), published in volume XV of the *Journal de l'École Polytechnique.* In his paper he showed that when a body moves in a rotating frame of reference, its motion relative to the frame of reference can be explained only if there is a force of inertia acting upon it. This inertial force causes the body to follow a path that curves to the right if the frame of reference is rotating counterclockwise and to the left if the rotation is clockwise. The inertial force came to be called the Coriolis force and is now known as the CORIOLIS EFFECT. It is of great importance in studies of the movements of air and of ocean currents. It is also relevant to ballistics, because missiles and projectiles traveling a long distance are subject to it.

Coriolis died in Paris on September 19, 1843.

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Croll, James

(1821–1890)
Scottish
Climatologist and geologist

A self-educated man, in 1864 James Croll proposed that the onset of GLACIAL PERIODS is triggered by changes in the ECCENTRICITY of the Earth's ORBIT and the PRECESSION OF THE EQUINOXES. This developed and extended earlier ideas and aroused great interest.

According to Croll, ice ages occur at intervals of 100,000 years, which is when the orbit reaches its maximum eccentricity. They are experienced alternately in the Northern and Southern Hemispheres, according to which hemisphere is having winter when the

Earth is farthest from the Sun. Although interest in his astronomical theory waned at the end of his life, Croll's work did much to prepare the way for the theory of MILANKOVITCH CYCLES, which is now widely accepted.

James Croll was born near Cargill, Perthshire, on January 2, 1821. The family was poor and James left school at 13. He read avidly, but needed to earn money and so worked at a succession of jobs: as a millwright, then a carpenter, in a tea shop, and as a hotelkeeper. He made and sold electrical goods and sold insurance. Finally, in 1857, he published a book, *The Philosophy of Theism,* which attracted some attention, and after working for a temperance newspaper in 1859 Croll was made the keeper—effectively the janitor—of the Andersonian Museum, in Glasgow. This gave him access to the library, where he continued his self-education. He published several papers on chemistry, physics, and geology, and in 1867 was placed in charge of the Edinburgh office of the Geological Survey of Scotland, a post he held until he retired, in 1880.

After his retirement Croll continued to work on his astronomical theory of climate change and on other topics that interested him. He published several books, including *Climate and Time, in Their Geological Relations* (1875), *Discussions on Climate and Cosmology* (1885), *Stellar Evolution and Its Relations to Geological Time* (1889), and *The Philosophical Basis of Evolution* (1890).

Croll died from heart disease near Perth on December 15, 1890.

Crutzen, Paul

(b. 1933)
Dutch
Atmospheric chemist

Professor Paul Crutzen shared with F. Sherwood Rowland and Mario J. Molina the 1995 Nobel Prize in chemistry, which was awarded for their discovery of the processes that deplete the OZONE LAYER.

Paul Crutzen was born on December 3, 1933, in Amsterdam, the Netherlands. His father, Josef Crutzen, was a waiter and his mother, Anna Gurk, worked in a hospital kitchen. Paul commenced his education in September 1940. In May of that year the Netherlands had been invaded and occupied by the German army, and Crutzen's primary education coincided with the period of occupation. His schooling was interrupted several times, and conditions were especially severe from the fall of 1944 until the country was liberated in May 1945. Nevertheless, he was able to complete his primary schooling, and in 1946 he entered the middle school, where he prepared to enter university. He specialized in mathematics and physics, languages, and was keen on sports, especially long-distance skating on the Dutch lakes and canals.

Unfortunately, illness meant that Crutzen did not achieve the grades in his final examinations that would have won him a grant to pay for a university education. Instead of embarking on a four-year university course he enrolled at a technical school for a three-year course in civil engineering, lasting from 1951 until 1954. The second year was spent working for a civil engineering company to gain practical work experience, and he managed to live for two years on what he was paid.

On completing his course, Crutzen obtained a job with the Bridge Construction Bureau of the City of Amsterdam. He worked there from 1954 until 1958, with an interruption for his compulsory military service from 1956 to 1958. During his time there he met Terttu Soininen, a student of Finnish history at the University of Helsinki. They were married in February 1958 and made their home in Gävle, a town about 125 miles (200 km) north of Stockholm, Sweden, where Crutzen was then working for a construction company. Their two daughters, Ilona and Sylvia, were born in Gävle.

In 1958, Crutzen saw a newspaper advertisement for a computer programmer in the Department of Meteorology of the Stockholm Högskola (high school, and since 1961 Stockholm University). Despite knowing nothing at all about computer programming, he applied for the post and won it. At the beginning of July 1959, the Crutzen family moved to Stockholm and Paul embarked on a second career. The Department of Meteorology (now the Meteorology Institute) and the International Meteorological Institute that was associated with it were at the forefront of research, and they housed some of the fastest computers in the world.

Until 1966, Crutzen spent much of his time building and running some of the first weather prediction models, including one of a TROPICAL CYCLONE. High-level computer languages, such as Algol and Fortran, had not yet been developed, and all programs had to be written in machine code, using binary notation.

Because he worked at the university, Crutzen was able to attend some of the lectures. He had no opportunity to do laboratory work, however, and so he concentrated on mathematics, statistics, and meteorology. In 1963, he obtained his master of science degree in these subjects and in 1965 began to work for his doctorate. At that time he was assisting another scientist in a project to study the different forms (called allotropes) of OXYGEN in the upper atmosphere, and he chose to make stratospheric chemistry the subject for his doctoral thesis. He received his Ph.D. in 1968 and his D.Sc. (doctor of science, which is a higher degree than a Ph.D.) in 1973, for research into the photochemistry of ozone.

Crutzen left Stockholm in 1969 to work until 1971 as a European Space Research Organization fellow at the Clarendon Laboratory of the University of Oxford, England. From 1974 to 1980, he worked at Boulder, Colorado, on the Upper Atmosphere Project of the National Center for Atmospheric Research and as a consultant in the Aeronomy Laboratory of the Environmental Research Laboratories (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION). He was an adjunct professor in the Atmospheric Sciences Department of the University of Colorado from 1976 to 1981. In 1980, he was appointed director of the Atmospheric Chemistry Division of the Max-Planck Institute for Chemistry, at Mainz, Germany, and from 1983 to 1985 he was executive director of the Institute. He held a part-time professorship at the University of Chicago from 1987 until 1991, and since 1992 he has been a part-time professor at the Scripps Institution of Oceanography of the University of California.

Professor Crutzen has received many honors and holds honorary degrees from universities at York, Canada, Louvain, Belgium, East Anglia, England, and Thessaloniki, Greece.

Dalton, John

(1766–1844)
English
Meteorologist and chemist

John Dalton was born at Eaglesfield, near Cockermouth, Cumberland (now Cumbria), on September 6, 1766, the son of a weaver and the third of six children. His father, Joseph, was a devout member of the Society of Friends, and in accordance with Quaker practice at the time he did not register the date of his son's birth, so there is some uncertainty about it. John began his education at the Quakers' school in Eaglesfield. The teacher was John Fletcher, and when Fletcher retired in 1778 John took his place.

Three years later, in 1781, Dalton moved to Kendal, where he continued to earn his living as a teacher and became a headmaster. John Gough, a wealthy Quaker who was also a classicist and mathematician, befriended Dalton. Under his influence Dalton began to write articles on scientific topics for two popular magazines, the *Gentlemen's Diary* and *Ladies' Diary*. Gough also encouraged him to keep a diary of meteorological observations. Dalton began this diary in 1787 and made entries in it regularly for 57 years until his death. It contained more than 200,000 observations.

In the 18th century, only members of the Church of England were accepted as students at the universities of Oxford and Cambridge. As a Quaker, Dalton was excluded, and consequently he was very largely self-taught.

In 1793, Dalton moved to Manchester, where Gough had helped him obtain a position as a teacher of mathematics and natural philosophy at New College. He held this post until 1799, when the college was moved to York, and Dalton remained behind in Manchester as a private teacher of mathematics and chemistry.

Dalton's first publication on weather, *Meteorological Observations and Essays* appeared in 1793, but it did not sell well. In 1794, Dalton was elected to the membership of the Manchester Literary and Philosophical Society, and a few weeks later he delivered his first paper to the society, "Extraordinary Facts Relating to the Vision of Colours." Dalton and his brother were both color blind, and this was the first account of the way the world appears to someone with this condition. For a time color blindness was known as Daltonism. He also lectured to the society on the weather. Dalton became the honorary secretary and then president of the society, and after he resigned his teaching position in 1799 he lived for many years in a house the society bought for him and which he shared with the Reverend W. Johns.

In 1803, Dalton proposed the law of partial pressures, known as Dalton's law (*see* GAS LAWS). He discovered that the DENSITY of water varies with its TEMPERATURE, reaching a maximum at 42.5°F (6.1°C). In fact, water reaches its maximum density at 39.2°F (4°C), but Dalton was close. He studied what happens when substances dissolve in water and when gases mix, concluding that water and gases must consist of very small particles that intermingle, so the particles of a dissolved substance are located between water particles. In his book *New System of Chemical Philosophy,* published in 1808, he suggested that the particles of different elements have different weights. He compiled a list of these weights (relative atomic masses) and devised a system of symbols for the elements. These could be combined to represent compounds.

Dalton became very famous. He delivered two courses of lectures at the Royal Institution in London, the first in 1804 and the second in 1809–10. He was elected a fellow of the Royal Society in 1822. He became a corresponding member of the French Academy of Sciences, and in 1830 he was elected one of its eight foreign associates. In 1833, the government awarded him an annual pension of £150 and raised it to £300 in 1836. This was a substantial award that would have allowed Dalton to live comfortably at a higher standard than the one he chose for himself. It was also an unusual honor. British governments rarely recognized the worth of individuals in this way. Government support for science took the form then, as now, of providing funds for institutions and paying the salaries of scientists directly employed by government ministries and agencies.

Dalton spent almost all of his time in Manchester, working in his laboratory and teaching. Each year he visited the Lake District, in his native Cumbria, and occasionally he visited London. He made a short visit to Paris in 1822. His only recreation was the game of bowls, which he played every Thursday afternoon. (The English game of bowls is played on an absolutely level surface lawn [or an indoor equivalent]. It is the game Sir Francis Drake allegedly played on Plymouth Hoe as the Spanish Armada approached, and it has no connection to the game of bowling, derived from skittles.)

John Dalton died in Manchester on July 27, 1844, and a statue was erected in his memory. The house in which he lived for so long contained many of his records and other relics, but it was destroyed during a bombing raid in World War II.

Daniell, John Frederic

(1790–1845)
English
Meteorologist, chemist, and inventor

John Daniell was a prolific inventor and became one of the most eminent scientists of his day. He was born in London on March 12, 1790, the son of a lawyer. He was educated privately, mainly learning Latin and Greek. It is not certain whether he earned a degree from Oxford University or was awarded an honorary one. His education completed, he went to work in a sugar refinery and resin factory owned by a relative, where he was able to improve the technology being used.

In his spare time he attended Royal Institution lectures given by William T. Brande, the professor of chemistry. He met Brande, and the two became close friends. Between them they revived the fortunes of the Royal Institution, which were then at a low ebb. Daniell left the factory and became a scientist when, in 1813 at the age of 23, he was appointed professor of physics at the University of Edinburgh. He combined chemistry with the physics he researched and taught at the university, and for a time in 1817 he managed the Continental Gas Company, developing a new process for making gas by distilling resin dissolved in turpentine. This process was used for a time in New York. His interest in gases also extended to the atmosphere.

In 1820, he made his first major contribution to METEOROLOGY with his invention of a DEW point HYGROMETER that measured relative HUMIDITY. It comprised two bulbs made from thin glass that were connected by a tube. One bulb was filled with ether and held a THERMOMETER. When the temperature of the air in the other bulb changed, the ether in the other bulb was warmed or cooled and either evaporated or condensed. This caused WATER VAPOR to condense onto or evaporate from the bulb containing ether. The average temperature at which this happened was the dew point temperature. The Daniell hygrometer remained in use for many years.

In 1823, Daniell published a book describing his meteorological research, *Meteorological Essays*. In the same year he was elected a fellow of the Royal Society.

Daniell moved from Scotland to London in 1831, when he was appointed the first professor of chemistry and meteorology at King's College, which had recently been founded (it is now part of the University of London). Daniell remained in this post until his death.

Daniell was very active in the Royal Society. In 1830, he installed in the entrance hall a BAROMETER that used water to measure pressure. Over the following years, he made many observations with it.

Daniell investigated the climatic influence of solar radiation, the circulation of the atmosphere, and he pointed out the importance of maintaining a humid atmosphere in greenhouses. This revolutionized greenhouse horticulture, and in 1824 Daniell was awarded the silver medal of the Horticultural Society.

His interest in chemistry and physics had not diminished, and in the 1830s Daniell became increasingly interested in electrochemistry. This led to his invention, in 1836, of the Daniell cell, the first reliable source of direct-current electricity.

On March 13, 1845, Daniell suffered a heart attack and died while attending a meeting of the Council of the Royal Society in London.

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Dansgaard, Willi

(b. 1922)
Danish
Geophysicist and paleoclimatologist

Willi Dansgaard is professor emeritus of geophysics at the University of Copenhagen.

Dansgaard was the first scientist to demonstrate that measurements of OXYGEN isotope ratios and the ratio of HYDROGEN and deuterium, also called heavy hydrogen, could reveal information about past climates. In 1966, scientists obtain the first ICE CORE from Greenland, and Dansgaard led a team of paleoclimatologists who analyzed the isotopic composition of the ice. Dansgaard also led the work to perfect the dating of ice layers in ice cores and to measure DUST particles trapped in the ice, and the acidity of the ice. In subsequent years, Dansgaard organized or participated in 19 expeditions to the GLACIERS of Norway, Greenland, and Antarctica.

Professor Dansgaard has received many awards, including the 1996 Tyler Prize for Environmental Achievement.

Darcy, Henri-Philibert-Gaspard

(1803–1858)
French
Civil engineer

Henri Darcy (sometimes called Henry Darcy) improved the PITOT TUBE (invented by the French physicist Henri Pitot, 1695–1771). He also discovered the law (DARCY'S LAW) governing the rate at which water flows through an AQUIFER.

Henri Darcy was born in Dijon, France, on June 10, 1803. His father, Jacques Lazare Darcy, was a civil servant and tax collector, and Henri's younger brother, Hugues, also became a civil servant and prefect (the principal administrative officer of a French district, or département). Jacques Darcy died in 1817, when Henri was 14 years of age, leaving his mother, Agathe Angelique Serdet, with only a small pension. She struggled to obtain the best possible education for her son, borrowing money to hire tutors and gaining a scholarship for Henri to attend college. When he was 18, Henri was admitted to the prestigious École Polytechnique in Paris, and when he was 20, in 1823, he entered the École des Pont et Chaussées (School of Bridges and Highways). After graduating, the Imperial Corps of Bridges and Highways employed Henri in Dijon.

In 1828, Henri married Henriette Carey, an English girl from Guernsey, one of the Channel Islands, who was living in Dijon. They remained together until Henri's death, but had no children.

The same year that he married, Henri was assigned to a project to provide the city with a reliable water supply. They dug a deep well, but found insufficient water, and Henri set about finding a better supply. This led him to supervise the construction of a system of pipes that carried spring water to reservoirs and 17 miles (28 km) of pipes that carried water under pressure to important public buildings and to 142 street pumps. The entire system was driven by gravity and required no pumps or filters. Darcy followed this with many other public works projects in and around Dijon. He also became active in the local government.

By 1848, Henri Darcy had risen to the post of chief engineer for the département of Côte d'Azur. He left Dijon and became chief director for water and pavements in Paris. That is where he conducted the research into liquid flow through pipes that led him to improve the design of the pitot tube.

Failing health compelled him to resign his post in 1855. He returned to Dijon, where he devoted himself to private research into topics that interested him. These established Darcy's law for the flow of water through a column of sand.

During a trip to Paris, Henri Darcy fell ill with pneumonia. He died on January 3, 1858. He is buried in Dijon.

Geer, Gerhard Jacob de

(1858–1943)
Swedish
Geologist

Gerhard (or Gerard) de Geer discovered VARVES (*varv* is the Swedish word for layer), thereby making an important contribution to the study of climate change. He also made other important contributions to QUATERNARY geology and the dating of sedimentary rocks. It was de Geer who coined the term *geochronology,* which is the scientific identification of geological time intervals.

Gerhard de Geer was born in Stockholm on October 2, 1858. His family was descended from Dutch aristocrats who had settled in Sweden early in the 17th century. The de Geer family was prominent in Swedish life. Gerhard was a member of the Swedish parliament (1900–05), and both his father and elder brother were prime ministers of Sweden.

While still a student at Uppsala University, in 1878 de Geer joined the Swedish Geological Survey, marking the commencement of his life's work of studying the Quaternary rocks and landforms of southern Sweden. By the time he graduated in 1879, de Geer had already noted that the laminations in sediments deposited at the edges of lakes as the ice retreated at the end of the last glacial period resembled TREE RINGS. He concluded that both the lakeside laminations and tree rings were probably formed annually. He pursued this study through the 1880s, publishing his first brief account of the work in 1882 and making a more formal presentation to the Swedish Geological Society in 1884. His work attracted international interest following the 11th International Geological Congress in 1910. The congress was held in Stockholm, and de Geer presided over it. It was in the paper he presented to the congress that de Geer first used the term *varves.* De Geer also studied glacial moraines, RAISED BEACHES, and changes in sea level associated with GLACIOISOSTASY.

Gerhard de Geer became professor of geology at Stockholm University in 1897, and from 1902 until 1910 he was president of the university. He still pursued his study of varves, and in 1915 he matched Swedish varves with varves in Norway and Finland. Accompanied by his wife, Ebba Hult de Geer, and two assistants, Ernst Antevs and Ragnar Liden, de Geer traveled to the United States in 1920. When the others returned to Sweden, Antevs remained behind to study North American varve chronology. De Geer retired from teaching in 1924 and became the founder and director of the Geochronological Institute of Stockholm University.

In the 1930s, Antevs showed that de Geer's TELECONNECTIONS were mistaken. De Geer thought he was being deliberately misunderstood, and the dispute became increasingly bitter. Their disagreement coincided with the discovery of RADIOCARBON DATING, and scientific interest in varves diminished.

Gerhard de Geer died in Stockholm on July 24, 1943.

Deluc, Jean André

(1727–1817)
Swiss
Geologist, meteorologist, and physicist

Jean Deluc is principally remembered for having invented the dry pile, a type of electric battery, but his contributions to geology and METEOROLOGY were no less important. He was born in Geneva on February 8, 1727. Until he was 46, Deluc worked in commerce and politics and made scientific excursions among the Swiss mountains. Then, in 1773, he moved to England. He was elected a fellow of the Royal Society and appointed a reader to Queen Charlotte, a post that brought him an income but did not make excessive demands on his time. The post made him free to pursue his scientific interests.

In 1778 and 1779, Deluc published a six-volume work on geology, *Lettres physiques et morales sur les montagnes et sur l'histoire de la terre et de l'homme* (Physical and moral letters on mountains and on the history of the Earth and of man). In this he suggested that each of the six days of the biblical creation was an epoch.

Deluc also discovered that water is more dense at 40°F (4°C) than it is at either higher or lower temperatures. In 1761, he also found that the heat required to melt ice or vaporize liquid water does not raise their temperatures. This was the concept of LATENT HEAT discovered independently by Joseph Black at about the same time. Jean Deluc was also the first scientist to propose that the amount of WATER VAPOR that can be contained in a given space is independent of any other gases that may be present in that space. He invented a HYGROMETER, though not a very successful one, and he was the first to devise a way of measuring height by means of a BAROMETER. He showed that an increase in elevation is proportional to a decrease in the logarithm of the AIR PRESSURE, and that a change in elevation is also inversely proportional to the air temperature.

Jean Deluc died at Windsor, England, on November 7, 1817.

Dobson, Gordon Miller Bourne

(1889–1976)
English
Meteorologist

The scientist who devoted much of his career to studying the OZONE LAYER was born on February 25, 1889. He served in the Royal Flying Corps (precursor of the Royal Air Force) during World War I, attaining the rank of captain, and was director of the experimental department at the Royal Aircraft Establishment, Farnborough. In 1920, Dobson took up the position of lecturer in METEOROLOGY at the University of Oxford.

In collaboration with Professor Frederick Alexander Lindemann (later Lord Cherwell, 1886–1957), Dobson studied meteor trails. They discovered a region of the stratosphere (*see* ATMOSPHERIC STRUCTURE) where TEMPERATURE increases with altitude. Dobson inferred, correctly, that the rise in temperature was due to the absorption of ULTRAVIOLET RADIATION by atmospheric OZONE, and he determined to measure the concentration of stratospheric ozone. In order to do so, in 1924 he built a spectrograph in his workshop at home. He used the instrument through 1925 to monitor the ozone concentration. He found that the concentration changes with the seasons and there is a relationship between the ozone concentration and weather conditions in the upper troposphere and lower stratosphere. In the following years, he built and calibrated five more spectrographs, which were used in other European locations. In 1927 or 1928, Dobson built a spectrophotometer that was more sensitive than the earlier spectrographs. He was elected to a fellowship of the Royal Society in 1927.

Early in the 1930s, Dobson became interested in AIR POLLUTION. He helped develop reliable methods for measuring concentrations of SMOKE, SULFUR DIOXIDE, and other pollutants.

During World War II, Dobson studied stratospheric HUMIDITY in order to forecast the height at which aircraft CONTRAILS would form. In the course of this work, Dobson invented the first frost-point HYGROMETER. After the war, Dobson returned to the study of stratospheric ozone. In 1945, the University of Oxford conferred the title of professor on him. Dobson retired from the university in 1956, but continued to study ozone. He wrote his last paper in 1973 and made his last observation the day before he suffered the stroke from which he died six weeks later. Dobson died in Oxford on March 11, 1976.

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Doppler, Johann Christian

(1803–1853)
Austrian
Physicist

Doppler was an Austrian physicist who discovered the DOPPLER EFFECT. This was first tested in 1845 at Utrecht, in the Netherlands. A train carried a group of trumpeters in an open carriage past a group of musicians located beside the rail track. The stationary musicians reported a change in pitch as the trumpeters approached and receded.

Doppler was born in Salzburg and educated in Vienna as a physicist and mathematician. In 1835, he was appointed professor of mathematics at the State Secondary School in Prague and subsequently held professorships at the State Technical Academy, Prague, and the Mining Academy, Schemnitz. In 1850, he returned to Vienna as director of the Physical Institute and professor of experimental physics at the Royal Imperial University of Vienna.

He died in Venice, Italy, on March 17, 1853.

Ekman, Vagn Walfrid

(1874–1954)
Swedish
Oceanographer and physicist

Vagn Ekman was born in Stockholm on May 3, 1874. He was educated at the University of Uppsala, where he received his doctoral degree in 1902. His doctoral thesis described his research into the cause of a phenomenon first reported in the 1890s by the Norwegian arctic explorer Fridtjof Nansen (1861–1930).

Nansen had noticed that ICE drifting on the surface of the sea did not move in the direction of the wind, but at about 45° to the right of it. Ekman was able to relate the movement of wind-driven ocean currents to FRICTION between different layers of water and to the CORIOLIS EFFECT. Together these produced a change in the direction of currents with depth that became known as the EKMAN SPIRAL. A similar effect occurs in the atmosphere. In 1905, Ekman explained the spiral more fully in a paper titled "On the Influence of the Earth's Rotation on Ocean-Currents," published in the Swedish journal *Arkiv för Matematik, Astronomi och Fysik*.

After receiving his doctorate, in 1902 Ekman moved to Norway (which was still part of Sweden) to take up a post as an assistant at the International Laboratory for Oceanographic Research in Oslo (which was then called Christiania). He remained there until 1908, and while there he came to know Nansen.

Ekman returned to Sweden in 1910, as professor of mechanics and mathematical physics at the University of Lund, a post he held until he retired in 1939. Vagn Ekman died on March 9, 1954.

Elsasser, Walter Maurice

(1904–1991)
German-American
Physicist

Walter Elsasser is the scientist who developed the theory that the Earth's core acts as a dynamo, generating the magnetic field. Elsasser also pioneered the analysis of the magnetic field recorded in the orientation of rock particles as a tool for studying the history of crustal rocks. This has been of great importance in tracing the movements of continents (*see* PLATE TECTONICS) and the history of climate.

Elsasser was born on March 20, 1904, at Mannheim, Germany, and was educated at the University of Göttingen, where he obtained his doctorate in 1927. He then taught at the University of Frankfurt, but he left Germany in 1933, when the Nazis came to power. Elsasser spent three years in Paris and then moved to the United States and joined the staff of the California Institute of Technology. In 1940, he became an American citizen. In the course of his career Elsasser was professor of physics at the University of Pennsylvania, professor of geophysics at Princeton University, and a research professor at the University of Maryland.

Walter Elsasser died on October 14, 1991.

Fabry, Marie-Paul-August-Charles

(1867–1945)
French
Physicist

Charles Fabry was one of the most distinguished physicists of his generation, and one of the most famous. He was born at Marseilles on June 11, 1867, and after commencing his education in Marseilles in 1885 he enrolled at the École Polytechnique in Paris, graduating in 1889. He studied physics and mathematics, but became increasingly drawn toward astronomy and optics. After his graduation, Fabry moved to the University of Paris, where he obtained his doctorate in physics in 1892.

Fabry then spent two years teaching physics at lycées (high schools) in several cities before joining the staff at the University of Marseilles in 1894, where he devoted himself to teaching and pursuing his own research. In 1904, he was appointed professor of industrial physics.

In 1914, the French government called him to Paris to investigate interference in sound and light waves, and in 1921 Fabry moved to Paris permanently as professor of physics at the Sorbonne. Later, he combined this post with that of professor of physics at the École Polytechnique and director of the Institute of Optics. In 1935, he became a member of the International Committee on Weights and Measures. He retired two years later, in 1937.

It is not uncommon for a research scientist to find that further advances are impossible because the available instruments are inadequate. They cannot penetrate the phenomena being investigated deeply enough or provide sufficiently accurate measurements. In this situation the experimenter, who is the only person in a position to know precisely what is needed, often modifies an existing device or invents a new one. That is what Charles Fabry and his colleague the French physicist Albert Pérot (1863–1925) did in 1896. The instruments they invented were based on two perfectly parallel half-silvered plates. If the distance between the plates is fixed, the instrument is known as the Fabry–Pérot INTERFEROMETER and as the Fabry–Pérot etalon if the distance can be varied. These instruments break light into its constituent wavelengths with a much greater resolution than was possible with other devices. Fabry and Pérot spent 10 years designing, improving, and using them. The two colleagues were able to confirm the DOPPLER EFFECT for light in the laboratory, and they applied the instruments to a variety of astronomical questions.

A question of particular interest concerned the absorption of solar ultraviolet radiation (*see* SOLAR SPECTRUM) in the atmosphere. Clearly some atmospheric gas was filtering it, and in 1913 Fabry used the interferometer to discover the presence of abundant OZONE in the upper atmosphere.

Fabry died in Paris on December 11, 1945.

Fahrenheit, Daniel Gabriel (or Gabriel Daniel)
(1686–1736)
Polish–Dutch
Physicist

The scientist whose name is still used every day because of the TEMPERATURE SCALE he devised was born on May 14, 1686, in Danzig (now called Gdansk), an ancient city at the mouth of the Vistula River on the coast of the Baltic Sea. Culturally, the city is Polish, and it now lies deep inside Poland, but at various times in the past changes in frontiers have meant it lay in Prussia or, more recently, in Germany.

Daniel Fahrenheit began his education in Danzig, but in 1701 he moved to Amsterdam in order to learn a business. He became interested in the making of scientific instruments, and in about 1707 he left the Netherlands to tour Europe, meeting scientists and other instrument makers, and learning the craft he had chosen to follow. In the course of his travels, in 1708 he met the Danish astronomer Ole (or Olaus) Christensen Römer (1644–1710). Fahrenheit returned to Amsterdam in 1717, established his own business making instruments, and remained there for the rest of his life.

At that time there was intense scientific interest in studying the atmosphere and the weather it produced, but meteorologists were greatly hindered by the lack of a reliable THERMOMETER. Galileo had made thermometers, and Guillaume Amontons had improved on them, but both of their instruments relied on the expansion and contraction of air to raise and lower a column of liquid and they were highly inaccurate. Fahrenheit turned his attention to the problem.

His first thermometer used alcohol as the liquid. Unlike earlier designs, however, Fahrenheit filled the bulb with liquid, so changes in temperature were indicated by the expansion and contraction of the column of liquid, not changes in the volume of a pocket of air. This was a great improvement, but an alcohol thermometer cannot measure very high temperatures, because of the low boiling point of alcohol (pure ethanol boils at 172.94°F, 78.3°C). So Fahrenheit tried mixing alcohol and water. This raised the boiling point, but the volume of the mixture did not change at a constant rate as the temperature increased or decreased, which made the thermometer very difficult to calibrate. Finally, in 1714, Fahrenheit tried mercury. Mercury boils at a much higher temperature than water (673.84°F, 356.58°C) and freezes at a much lower temperature (-37.97°F, -38.87°C), so a mercury thermometer can be used over a much wider temperature range than can an alcohol thermometer. First, though, Fahrenheit had to devise a way to purify the metal, because impurities caused it to stick to glass surfaces. Once he had achieved this, he found that mercury changed its volume at a fairly constant rate with changing temperature, although it changed by a smaller amount than alcohol.

Having made a thermometer, Fahrenheit then had to calibrate it. Ole Römer had invented a thermometer in about 1701, and during his visit to Copenhagen Fahrenheit had watched him calibrate one. He based his calibration on the Römer temperature scale, using two fixed, or fiducial, points. After some later adjustments, he produced the Fahrenheit temperature scale that is still in use today, on which ice melts at 32°, water boils at 212°, and average body temperature is 98.6°.

Fahrenheit's thermometer was far more reliable and accurate than any that had existed before, and the mercury thermometers in use today are made in the way Fahrenheit devised, although the use of mercury is being phased out because exposure to the metal is harmful to health. Amontons had earlier suggested that water always boils at the same temperature. Fahrenheit set out to check this and found it to be true, but only if the AIR PRESSURE remains constant. He also examined many other liquids and found all of them had characteristic boiling and freezing temperatures.

In 1724, Fahrenheit described his method for making thermometers in a paper he submitted for publication in the *Philosophical Transactions of the Royal Society.* He was elected to the Royal Society in the same year.

Fahrenheit died at The Hague on September 16, 1736.

Ferdinand II

(1610–1670)
Italian
Physicist

A member of the powerful Medici family, Ferdinand was born on July 14, 1610, the son of Cosimo II, grand duke of Tuscany. His father died in 1620. Ferdinand was 10 years old when he became ruler.

Ferdinand was not a strong ruler and was unable to protect Galileo from his trial by the Inquisition in 1633, but he took a keen interest in science, and especially in atmospheric science. One of the scientific challenges of the time was to find a way to measure TEMPERATURE. Galileo had attempted this with his air thermoscope (*see* THERMOMETER), and in 1641 Ferdinand improved on Galileo's instrument by inventing a thermometer consisting of a tube that contained liquid and was sealed at one end. He improved on this with a further design in 1654, his thermometer providing the basis for the improved design that would be made by Daniel Fahrenheit about 60 years later.

Ferdinand also designed one of the earliest accurate HYGROMETERS. It consisted of a tapering cylinder that was filled with ice. WATER VAPOR condensed on the outside of the cylinder and ran down it into a collecting funnel and from there to a flask. The amount of water that accumulated in the flask indicated the HUMIDITY of the air.

In 1657, the year he produced his hygrometer, Ferdinand and his brother Leopold founded the Accademia del Cimento (Academy of Experiments) in Florence. Members of the Accademia were especially interested in studying the atmosphere. Carlo Renaldini was one of those who worked on developing the thermometer. The Accademia itself was the forerunner of other scientific academies, including the Royal Society of London (founded in 1665) and the Royal French Academy of Sciences (founded in 1666). The Accademia ceased to function in 1667.

Ferdinand died on May 24, 1670, and was succeeded by his son, Cosimo III. Ferdinand's grandson, Gian-Gastone, had no male heir, and the Medici family ended with his death in 1737.

Ferrel, William

(1817–1891)
American
Climatologist

William Ferrel was born on January 29, 1817, in Bedford County, Pennsylvania. When he grew up, he earned his living as a school mathematics teacher, but he combined this with an intense interest in the TIDES and weather. His study of the circulation of the atmosphere led him to publish in 1856 a mathematical MODEL of the circulation of the atmosphere. He revised his model in 1860 and again in 1889. The model proposed the existence of a midlatitude cell. In this cell the vertical movement of the air is driven by the Hadley cell on the side nearest the equator and by the polar cell on the side nearest the pole. This third cell is known as the Ferrel cell (*see* GENERAL CIRCULATION).

In 1857, Ferrel's particular interest in and understanding of tides led to an invitation to join the staff of *The American Ephemeris and Nautical Almanac,* which was published in Cambridge, Massachusetts. While working for this publication Ferrel calculated that the combined effect of the PRESSURE GRADIENT FORCE and the CORIOLIS EFFECT must be to cause winds generated by a PRESSURE GRADIENT to flow at 90° to it, parallel to the isobars (*see* ISO-) rather than across them. A few months after he reached this conclusion, the Dutch meteorologist C. H. D. Buys Ballot announced the same phenomenon. Buys Ballot had not known of Ferrel's work, and when he learned of it he readily acknowledged Ferrel's prior claim. It was too late, however, and the discovery came to be known as BUYS BALLOT'S LAW.

On July 1, 1867, Ferrel was appointed to a position at the United States Coast and Geodetic Survey.

His task there was to develop the general theory of the tides to which he had already devoted a considerable amount of work and which he had advanced further than any of his contemporaries.

Winds and atmospheric pressure affect the tides, so Ferrel widened his study of tides to include relevant meteorological phenomena. This led him to a more general investigation of METEOROLOGY, and for some time he alternated between studying tides and studying weather.

William Ferrel wrote extensively on the subject of meteorology. His titles include *Meteorological Researches,* published in three volumes between 1877 and 1882, *Popular Essays on the Movements of the Atmosphere* (1882), *Temperature of the Atmosphere and the Earth's Surface* (1884), *Recent Advances in Meteorology* (1886), and *A Popular Treatise on the Winds* (1889).

On August 9, 1882, Ferrel tendered his resignation from the Coast Survey in order to accept a position in the Army Signal Service. The superintendent accepted his resignation, and Ferrel continued to work for the Signal Service until his retirement in 1886. The Signal Service already had an interest in meteorology, and in November 1870 its newly established Division of Telegrams and Reports for the Benefit of Commerce became a national weather service.

The acceptance of Ferrel's resignation from the Coast Survey was conditional. He was asked to complete the investigations on which he was engaged at the time, and he was also asked to continue supervising the tide-predicting machine he had invented. This was a mechanical device, worked by levers and pulleys, that took account of 19 constituents of the forces affecting tides and gave readings, on five dials, of the predicted times and heights of high and low water. Ferrel had submitted plans and an explanation of the machine to the Coast Survey in the spring of 1880, and in August of that year he described it in Boston at the annual meeting of the American Association for the Advancement of Science. The idea was accepted, but it proved difficult to find a machinist with the adequate skills. Work on constructing the device did not commence until the late summer of 1881, and the machine was not completed until the autumn of 1882. The tide-predicting machine was first used to predict the tides for 1885, and it remained in use until 1991. Computers are now used to predict tides.

After his retirement, William Ferrel moved to Maywood, Kansas, where he died on September 18, 1891.

FitzRoy, Robert
(1805–1865)
English
Naval officer, hydrographer, and meteorologist

In 1860, *The Times* of London became the first newspaper in the world to publish a daily weather forecast. That forecast was prepared by Admiral FitzRoy, the Head of Meteorology at the Board of Trade. This was the department that was to become the British METEOROLOGICAL OFFICE.

Robert FitzRoy was born on July 5, 1805, at Ampton Hall, in Suffolk, an English county to the northeast of London. He was an aristocrat, the grandson on his father's side of the duke of Grafton and on his mother's side of the marquis of Londonderry, and directly descended from King Charles II. FitzRoy was educated at the Royal Naval College, Portsmouth. After graduating, on October 19, 1819, he entered the Royal Navy, and he received his commission as an officer on September 7, 1824.

FitzRoy served in the Mediterranean and was then sent to South America on board HMS *Beagle,* which was conducting a surveying mission. When the captain of the *Beagle* died, FitzRoy assumed command, completing the survey and returning safely to England. He applied to lead a second survey, and in 1831 the Naval Hydrographer, Admiral Sir Francis Beaufort, granted the request. FitzRoy sailed once more as captain of the *Beagle,* this time accompanied by Charles Darwin.

The *Beagle* was well equipped for its scientific mission, and the equipment included several BAROMETERS. FitzRoy used these to prepare short-term weather forecasts. In another innovation, this was the first voyage in which wind observations recorded in the log were based on the BEAUFORT WIND SCALE. A well-trained and experienced sailor, FitzRoy knew how important it was to predict the weather.

With the survey complete, the *Beagle* arrived back in Portsmouth on October 2, 1836, and FitzRoy settled down to write his accounts of the voyage. These were published in 1839 (as two volumes of *Narrative of the Surveying Voyages of His Majesty's Ships* Adventure *and* Beagle *Between the Years 1826 and 1836, Describing Their Examination of the Southern Shores of South*

America, and the Beagle*'s Circumnavigation of the Globe*). FitzRoy was elected a fellow of the Royal Society for his surveying work.

By then an admiral, in 1841 Robert FitzRoy became a Member of Parliament for Durham, and in 1843 he was made governor general of New Zealand. He was recalled from New Zealand in 1845 at the insistence of the British settlers, mainly because he believed the Maori claims to land were as legitimate as theirs. Admiral FitzRoy retired from active service in 1850. In 1854, he took up his post at the Meteorological Office and devoted himself wholly to METEOROLOGY.

At the Meteorological Office, FitzRoy encouraged the collection of weather observations, established barometer stations, and used TELEGRAPHY to gather data. These allowed the Meteorological Office to issue weather forecasts and, in 1861, the first storm warnings. In 1863, FitzRoy published *The Weather Book,* in which he set out principles to guide sailors in WEATHER FORECASTING.

These included 47 "instructions for the use of the barometer to foretell weather." FitzRoy believed a barometer should be installed at every port. Sailors could examine the instrument, use FitzRoy's instructions to interpret the reading, and then decide whether or not to set sail. "FitzRoy" barometers became very popular, and Fitzroy himself invented some versions. There were domestic versions with THERMOMETERS, STORM GLASSES, and various other devices added to them, as well as a set of the admiral's instructions. FitzRoy barometers were still being manufactured in the early 20th century, and reproductions are still made.

FitzRoy's work saved many lives, but criticisms of his forecasting methods by the eminent meteorologist Matthew Maury and of his humanitarian political beliefs by newspapers and politicians greatly troubled him. He also experienced conflict between his strongly held religious views and Darwin's theory of evolution by natural selection, which he had helped to develop. Unable to resolve these difficulties, on April 30, 1865, he committed suicide at his home at Upper Norwood, near London, by cutting his throat.

Flohn, Hermann

(1912–1997)
German
Meteorologist and climatologist

Hermann Flohn, designer of the widely-used climate classification system (*see* FLOHN CLASSIFICATION), was born at Frankfurt-am-Main on February 19, 1912. He was educated at the Universities of Frankfurt and Innsbruck, graduating from both in METEOROLOGY, geography, geophysics, and geology.

Flohn worked at the University of Marburg for a few months, and in 1935 he joined the German state weather service and moved to Berlin. During World War II, Flohn served in the Luftwaffe (air force) meteorological service. He was captured and became a prisoner-of-war.

After the war, Flohn joined the German weather service and was based at Bad Kissingen. He was head of research at the weather service from 1952 to 1961, and from 1961 until 1977 he was a professor at the University of Bonn and director of the Meteorological Institute.

After his retirement in 1977, Hermann Flohn was made professor emeritus and continued to head research projects. The last of these was conducted on behalf of the North Rhine–Westphalia Academy of Science. It investigated large-scale climate forecasting and its environmental significance.

Hermann Flohn died in Bonn on June 23, 1997.

Fortin, Jean-Nicholas

(1750–1831)
French
Instrument maker

Many eminent scientists used precision instruments Jean Fortin had made, but Fortin is best known for the portable mercury BAROMETER that he invented and that bears his name.

Fortin was born at Mouchy-la-Ville, near Paris, on August 8, 1750. No record survives of his education, but as a young man he worked for a time at the Bureau de Longitudes in Paris. Later he worked at the Paris Observatory, where he made astronomical and surveying instruments.

In 1800, Fortin made his first portable barometer. The instrument had a leather bag filled with mercury, a cistern containing a glass cylinder, a pointer to mark the level of the mercury, and a means of adjusting the mercury level to zero. Fortin did not invent any of these features, but he was the first instrument maker to combine all of them in one barometer.

Jean Fortin died in Paris in 1831.

Fourier, Jean-Baptiste-Joseph
(1768–1830)
French
Mathematician and Physicist

Jean Fourier was born on March 21, 1768, at Auxerre, France, a town to the southeast of Paris. His father was a tailor. Jean was orphaned when he was eight, but the bishop exerted his influence to have him admitted to the Auxerre military academy, where boys were educated to become artillery officers. It was there that Jean first encountered mathematics and demonstrated that he had an enthusiasm and great aptitude for the subject.

His humble origin meant he was unable to become an artillery officer, so when he left the academy he went to a Benedictine school in St. Bênoit-sur-Loire. He returned to Auxerre in 1784 and taught mathematics at the military academy. When the French Revolution began in 1787, Fourier took an active part locally, but he did not support the Terror that came later. Despite his initial support, Fourier was arrested in 1794, but was released after a few months, following the execution of Robespierre.

The École Normale opened in Paris in 1795, and Fourier taught there, acquiring such a reputation that it was not long before he was made professor of analysis at the École Polytechnique. In 1798, he was one of the learned advisers, called *savants,* chosen to accompany Napoleon on his campaign in Egypt. Fourier was made governor of lower Egypt and remained there until 1801.

On his return to France, Fourier was made prefect (chief administrator) of the département of Isère and lived at Grenoble, in the south of the country. In 1808, Napoleon conferred the title of baron on him and later made him a count. Fourier rejoined Napoleon in 1815, and after Napoleon's final defeat the following year he settled in Paris.

Fourier was elected to the Academy of Sciences in 1817, and in 1822 he became its joint secretary, sharing the position with the zoologist Georges Cuvier (1769–1832). He was also elected to the Académie Française and to foreign membership of the Royal Society of London.

Fourier had resumed his mathematical studies during the years he lived in Grenoble. He was particularly interested in the conduction of heat and sought to describe this in purely mathematical terms. He explained the theory he had devised to do so in *Théorie Analytique de la Chaleur.* Published in 1822 and translated into English (*Analytical Theory of Heat*) in 1872, this proved to be one of the most influential scientific books of the 19th century.

The rate of conduction varies with the temperature gradient, as well as with the composition of the material and the shape of the conducting body. In order to comprehend this, Fourier developed what came to be known as Fourier's theorem. This is a technique that allows the overall description to be broken down into a series of simpler, trigonometric equations, known as the Fourier series, the sum of which is equal to the original description. The Fourier series can be applied to any complex function that repeats and so it is of value in many branches of physics. It is widely used by meteorologists. Fourier also developed the use of linear partial differential equations for solving boundary-value problems. This, too, is relevant to numerical WEATHER FORECASTING.

His theorem and series were only part of Fourier's contribution to mathematics. He also investigated probability theory and the theory of errors.

Fourier had contracted an illness while he was in Egypt, which may explain his conviction that the heat of the DESERT was beneficial. He lived wrapped up in thick, warm clothes in overheated rooms. He died in Paris on May 16, 1830.

Franklin, Benjamin
(1706–1790)
American
Statesman, physicist, inventor, author, and publisher

One of the best-known and most admired men in the world during the second half of the 18th century, Franklin's achievements were summarized by the French economist Anne-Robert-Jacques Turgot (1727–81) in the words: "He snatched the lightning from the skies and the scepter from tyrants." To Americans he is known as one of the founding fathers, but he is no less famous in Europe. There, in his own day, he was known mainly as a natural philosopher—a person who would nowadays be called a scientist.

Franklin was a complex man, with many sides to his personality, but his attitude to science was expressed in a letter he wrote in 1780 to the English chemist Joseph Priestley (1733–1804): "The rapid progress true science now makes occasions my regretting sometimes that I was born too soon. It is impossible to imagine the height to which may be carried, in a thousand years, the power of man over matter. . . . O that moral science were in as fair a way of improvement, that men would cease to be wolves to one another, and that human beings would at length learn what they now improperly call humanity!"

Benjamin Franklin was born on January 17, 1706, in Boston, Massachusetts. His father, Josiah, a soap and candle maker, had emigrated from Banbury, Oxfordshire, in England. It was a large family—Benjamin was the 15th of 17 children. The family could not afford to send him to college, and he spent only one year at a grammar school. He was educated privately, but was mainly self-taught.

Franklin's greatest scientific achievements arose from his study of electricity. In 1745, the German physicist Ewald Jurgen (George) von Kleist (1700–48) had discovered a way to condense electric charges. His device was first investigated thoroughly by the Dutch physicist Pieter van Musschenbroek (1692–1761) at the University of Leiden (or Leyden) in the Netherlands, and so it became known as a Leyden jar. It consists of a glass jar lined on the inside with metal and sealed by a cork through which a metal rod is inserted. There were already machines that used friction to produce static electrical charges, and the Leyden jar was very good at storing these charges. The stored charge would be discharged as a spark if a hand was brought close to the metal rod, and if enough charge had accumulated, anyone approaching too closely would receive a strong electric shock. If a metal object was brought close to the rod, a spark would leap across the gap and there would be a loud crackling noise.

Like many other scientists, Franklin experimented with a Leyden jar. His observations led him to wonder whether the spark and crackle might not be a tiny demonstration of LIGHTNING and THUNDER and, therefore, whether during a THUNDERSTORM the sky and Earth might become a giant Leyden jar.

It was an idea that needed testing, and to do so Franklin performed the most famous of all his experiments—and by far the most dangerous. In 1752, he flew a kite in a thunderstorm. He had attached a pointed piece of wire to the kite and tied a long silken thread to the wire. At the bottom of the thread he tied a metal key. As the kite flew near the base of the storm cloud and lightning began flashing nearby, Franklin held his hand close to the key and a spark jumped from the key to his hand. Then he held a Leyden jar to the key, and it accumulated an electric charge. Franklin had proved that lightning is a discharge of electricity and thunder is the sound of the spark. In the same year, the French scientist Thomas-François d'Alibard (1703–99) also proved, independently of Franklin, that lightning is an electrical phenomenon.

Franklin was extremely lucky. The next two people to repeat his experiment were killed, and on no account should anyone try to perform it.

Franklin had also noticed that electricity sparks more readily and over a greater distance if there is a pointed surface toward which it can travel. This led him to suggest that buildings could be protected from damage by lightning if pointed metal rods were fixed to their roofs and connected to the ground—earthed—by metal wires. He had invented the lightning conductor, and these were soon being fitted throughout America. Franklin's lightning conductors saved many lives and much damage to property was avoided.

Franklin did make one mistake. It was known that there are two types of electricity and that they repelled or attracted each other, apparently on the principle of like repelling like and opposites attracting each other. This might be explained, Franklin thought, if electricity is some kind of fluid—a gas, perhaps—that can be present either in excess or in deficiency. Then, two bodies each of which contained either an excess or a deficiency of it would repel each other. If one body had an excess and the other a deficiency, on the other hand, they would attract each other and electricity would flow from the excess to the deficiency. This is wrong, of course, because electricity is not a fluid. We do retain a little of the terminology Franklin introduced, however. He proposed that an excess of the fluid be called "positive" electricity and a deficiency "negative" electricity.

At the end of a very long and very distinguished political, diplomatic, and scientific career, Benjamin Franklin retired to Philadelphia at the age of 79. Already ill, he was bedridden for the last year of his life. He died on April 17, 1790. He was given the most impressive funeral there had ever been in Philadelphia; in France, many eulogies were composed to the man the French regarded as the embodiment of freedom and enlightenment.

Fujita, Tetsuya Theodore
(1920–1998)
Japanese–American
Meteorologist

Tetsuya Fujita, who became one of the world's leading authorities on TORNADOES, was born on October 23, 1920, in the town of Sone, on the Japanese island of Kyushu. In April 1939, he enrolled at Meiji College of Technology, graduating in June 1943 with a degree in mechanical engineering. In September of that year he was appointed assistant professor of physics at Meiji College. In 1949, the college became the Kyuhsu Institute of Technology.

A few months after atomic bombs fell on Hiroshima and Nagasaki, Fujita visited those cities to survey the damage and from that to calculate the number of bombs that had been used and the height at which they had detonated. In 1947, he studied DOWNDRAFTS in THUNDERSTORMS, and in 1948 he made his first detailed study of a tornado. Also in 1948, Fujita married Tatsuko Hatano. He conducted his first study of a TROPICAL CYCLONE in 1949.

In May 1951, Fujita commenced his research for a doctorate in science at the University of Tokyo. He completed his research in 1952 and was awarded his D.Sc. in 1953. Fujita then accepted a two-year research appointment at the University of Chicago, where he arrived on August 13, 1953. He returned to Japan in 1955 to obtain an immigrant visa to the United States, and in 1956 he returned with his family to become research professor and senior meteorologist at the University of Chicago.

His first major tornado study was of one that had struck Fargo, North Dakota, in 1957. There were still photographs and movies of that tornado, as well as detailed records of the damage it caused. These allowed Fujita to describe the life cycle of the tornado. In 1962, Fujita was appointed associate professor at the university, and he became a professor of METEOROLOGY in 1965.

Fujita was divorced in 1968, and in the same year he became a United States citizen and added Theodore to his name. From that time he was known as Ted to his friends. In 1969, he married Sumiko Yamamoto, and in February 1971 she collaborated with him and Allen Pearson, formerly the chief tornado forecaster for the NATIONAL WEATHER SERVICE, in developing the FUJITA TORNADO INTENSITY SCALE.

In October 1971, after witnessing a large DUST DEVIL, Fujita proposed the existence of suction vortices (*see* TORNADO). Despite his intense interest in tornadoes and his deep understanding of them, it was not until June 12, 1982, that he saw one for the first time—in fact several of them, in Denver, Colorado. There was a serious air crash in June 1975, and after studying what had happened, Fujita began investigating other crashes in order to find a way of identifying and avoiding MICROBURSTS—at a time when many scientists denied their existence.

Ted Fujita retired in September 1990, but continued to study atmospheric phenomena, and especially tropical cyclones and El Niño (*see* ENSO). In 1995, the first of a series of illnesses weakened his health. He died in his sleep at his home in Chicago on November 9, 1998.

Galilei, Galileo
(1564–1642)
Italian
Physicist and astronomer

One of the most famous scientists who has ever lived, Galileo is usually identified by his given name rather than by his family name, Galilei. His father was Vincenzio Galilei (ca. 1520–91), a musician and mathematician. Galileo was born at Pisa on February 15, 1564.

He received his first lessons from a private tutor. Then, in 1574, the family moved to Vallombrosa, near Florence, and Galileo continued his education at a monastery there. In 1581, he enrolled to study medicine at the University of Pisa, but the family could not afford the expense, and in 1585 he returned home without having taken a degree.

While at the university, Galileo's interest had turned toward mathematics and physics, and by the time he had to leave he had started to study these subjects. A popular story has it that Galileo once watched a lamp that was swinging in the cathedral at Pisa and noticed that no matter how large the range of its swing, the lamp always took the same amount of time to complete an oscillation. He timed the swings by counting his pulse beat. Later in life he confirmed this observation experimentally and suggested that the principle of the pendulum might be applied to the regulation of clocks.

Following his return to Florence, Galileo obtained a post as a lecturer in mathematics and science at the

Florentine Academy, at the same time continuing his studies of Euclid (flourished ca. 300 B.C.E.) and Archimedes (287–212 B.C.E.). In 1586, Galileo invented an improved version of a balance first devised by Archimedes that was used to measure specific gravity. At about this time his father was measuring the lengths and tensions in the strings of musical instruments that produce particular intervals between notes, and this may have helped convince Galileo that mathematical descriptions of phenomena could be tested by experiment.

Galileo became professor of mathematics at the University of Pisa in 1589. The appointment was an honor for him, but it was poorly paid, and in 1592 he applied for and was awarded the better-paid post of professor of mathematics at the University of Padua. He remained at Padua for the next 18 years, and it is there that he did most of his best work.

As well as his experiments with gravity and motion and his astronomical observations and calculations, Galileo maintained the interest in the behavior of fluids that had begun with his studies of the work of Archimedes. In 1593, he invented the first THERMOMETER—called an air thermoscope. It consisted of a bulb filled with air that was connected to a vertical tube containing a column of water. As the temperature rose and fell, the air in the bulb expanded and contracted, pushing the water up the tube or allowing it to fall. Unfortunately, the air thermoscope was highly inaccurate, because no account was taken of changes in atmospheric pressure. Nevertheless, this was one of the earliest attempts to make an instrument for making scientific measurements. Toward the end of his life, Galileo became interested in discovering whether air is a physical substance having mass. A young assistant, Evangelista Torricelli (1608–47), set to work on the problem and the experimental apparatus he devised was the first BAROMETER.

Galileo had little time for those who disagreed with his observations or the arguments he based on them. He was combative and could be sarcastic, but with good reason. He was convinced that natural phenomena can be described mathematically and that observation and experiment can then be used to validate the mathematical description. He was establishing what is now accepted as the basis of scientific procedure, but to do so he had to overthrow the prevailing verbal and nonmathematical approach that was derived from the work of Aristotle.

Galileo's fame rests on three achievements. He was the first person to use a telescope to study the night sky. His observations provided evidence with which he supported the conclusion of Nicolaus Copernicus (1473–1543) that it is the Earth which orbits the Sun and not the reverse and therefore that the Sun, not the Earth, is at the center of what was then thought of as the whole universe. His studies of motion and gravitation outlined the principles Isaac Newton (1642–1727) later formalized as the laws of motion. His final achievement, and perhaps the most important, was his application of mathematics to the study of natural phenomena.

His support for the ideas of Copernicus led Galileo into conflict with the church, and in 1633 he was found guilty of heresy and sentenced to remain for the rest of his life in his villa at Arcetri, near Florence. He continued to study, experiment, and write, summarizing his early experiments and his thoughts on mechanics in *Discorsi e Dimonstrazione Matematiche Intorno a Due Nuove Scienze* (*Discourses and Mathematical Demonstrations Concerning Two New Sciences*), a book that was smuggled out of Italy and published in Leiden, the Netherlands, in 1638.

Galileo became blind in 1637, but even this did not stop him working. He finally designed a pendulum-driven clock that was built in 1656 by Christiaan Huygens (1629–95) and he directed the work of his assistants. He was still dictating to them when he fell ill with a fever toward the end of 1641. Galileo died at Arcetri on January 8, 1642.

Galton, Francis

(1822–1911)
English
Scientist, inventor, and explorer

Sir Francis Galton was the first scientist to plot meteorological data onto a WEATHER MAP and to attempt to produce a SYNOPTIC chart showing the weather conditions over a wide area. He played a large part in preparing the daily weather charts that were published by *The Times* of London from data supplied by the METEOROLOGICAL OFFICE. This was one of several contributions he made to the scientific study of weather.

Galton was born into a Quaker family on February 16, 1822, near Sparkbrook, now a suburb of Birmingham, England, and was the youngest of the nine children of a wealthy banker. He was also a first cousin of Charles Darwin (1809–82). Francis was able to read before he was three years old, and by the time he was four he was studying Latin.

In response to his father's wishes Francis Galton studied medicine at Birmingham General Hospital and then at King's College, London, but he interrupted his medical studies to study mathematics at Trinity College, Cambridge. After that he resumed studying medicine at St. George's Hospital, London, but he never completed the course. His father died, and Francis inherited a fortune, so he left the hospital, and for the rest of his life he pursued whatever topic interested him.

First he traveled through the Balkans, Egypt, Sudan, and the countries at the eastern end of the Mediterranean. He spent 1850 and 1851 on a journey of 1,700 miles (2,735 km) through southwestern Africa, after which he visited Spain. His observations in what was then a little known part of Africa led to the award of the Gold Medal of the Royal Geographical Society in 1854, and in 1856 he was elected a fellow of the Royal Society.

His travels ended, in the 1860s Galton began to study the weather. In particular, he wondered whether it might be possible to detect large-scale patterns in the weather and, from these, to forecast weather. He circulated a detailed questionnaire to WEATHER STATIONS in different parts of the British Isles, asking for information about the weather conditions that had prevailed through the month of December 1861. When the replies arrived, he plotted them on a map, using symbols he invented for the purpose. In 1862, he finally succeeded in compiling a detailed weather map. This showed a previously unsuspected relationship between atmospheric pressure and the speed and direction of wind.

Galton was familiar with the work of Matthew Maury (1806–73) and Admiral FitzRoy (1805–65). He also knew that the French astronomer Urbain-Jean-Joseph Leverrier (1811–77) issued daily weather charts of the North Atlantic based on observations from ships and coastal stations, although these were so unevenly distributed that the charts included a great deal of guesswork. Maury, FitzRoy, and Leverrier had established the cyclonic circulation of air around a center of low pressure (*see* CYCLONE). Galton's questionnaire revealed its opposite: anticyclonic circulation around a center of high pressure. Galton coined the term *ANTICYCLONE,* in a paper he submitted to the Royal Society. He published the results of his research in 1863 in a monograph titled *Meteorographica* (published by Macmillan) and summarized them, much later, in his 1908 book *Memories of My Life* (published by Methuen).

As well as preparing weather charts for publication, in *The Times* and in *Meteorographica,* Galton helped find a way to print them using movable type. He had typefaces designed for the purpose and modified a drawing instrument called a pantograph so it used a drill to score curves and arrows in a soft material that could be used to make casts for printing.

Meteorologists were beginning to study the upper air by means of small balloons and kites to which instruments were attached. Galton had the idea of measuring the speed and direction of the wind at a specified location and time by means of the smoke emitted by an exploding shell. Galton was closely associated with the Meteorological Office, and the shell was designed and fired experimentally under their auspices. The experiment was carried out over an area of the Irish coast where no ships might be damaged by falling debris, and it was very successful. The shells exploded consistently at 9,000 feet (2,745 m), releasing a cloud of smoke Galton was easily able to track. On the suggestion of FitzRoy, Galton also invented the WIND ROSE.

In addition to his contributions to METEOROLOGY, Francis Galton was the first person to demonstrate the uniqueness of fingerprints (though that uniqueness has still not been proved) and partly worked out a system for identifying them. He invented a teletype printer and the ultrasonic dog whistle, and also devised new techniques for statistical analysis, as well as a word-association test that was adopted by Sigmund Freud (1856–1939).

Galton's main interest, stimulated by his cousin's book *On the Origin of Species by Means of Natural Selection,* lay in measuring the mental abilities of people and determining the extent to which these were inherited. From this he hoped it might be possible to improve them by means of selective breeding. This project was called eugenics, and although it is now discredited Galton's contribution to it was of great importance to the scientific study of psychology.

Francis Galton was knighted in 1909. He died at Haslemere, Surrey, on January 17, 1911.

Gay-Lussac, Joseph-Louis

(1778–1850)
French
Chemist and physicist

Joseph Gay-Lussac was born on December 6, 1778, at St. Léonard, Haute Vienne, in central France. His father was a judge named Antoine Gay, who added Lussac to the name to avoid confusion with other families called Gay. Lussac was the name of an estate near St. Léonard. Antoine was arrested in 1793 for showing sympathy to the aristocrats.

Joseph began his education locally, and in 1797 he enrolled at the École Polytechnique in Paris, transferring in 1799 to the École des Ponts et Chaussées (School of Bridges and Highways), from which he graduated in 1800. His interest was in engineering, but while still a student Gay-Lussac began to assist the distinguished French chemist Claude-Louis Berthollet (1748–1822), working at Berthollet's home at Arcueil, near Paris. Berthollet was very famous, and his home was a meeting place for many of the leading scientists of the day. For a time, Gay-Lussac worked alongside Bertollet's son in a factory where linen was bleached.

In 1802, Gay-Lussac was appointed a demonstrator in chemistry at the École Polytechnique. He spent 1805 and 1806 on an expedition to measure terrestrial magnetism led by Alexander von Humboldt (1769–1859). In 1808, he married Geneviève Rojet, and on January 1, 1810, he became professor of chemistry at the École Polytechnique. He was also professor of physics at the Sorbonne University in Paris, a position he held from 1808 until 1832, when he resigned to take up the post of professor of chemistry at the Musée National d'Histoire Naturelle, in the Jardin des Plantes. In 1806, he was made a member of the Academy of Sciences.

Gay-Lussac was also a politician. In 1831, he was elected to the chamber of deputies to represent his home département of Haute-Vienne, and in 1839 he was made a peer and entered the chamber of peers, which was then the upper house of the French parliament.

Gay-Lussac published his first research results in 1802. In collaboration with his friend Louis-Jacques Thénard (1777–1857), Gay-Lussac had formulated a law stating that when the TEMPERATURE is increased by a given amount, all gases expand by the same fraction of their volume. Jacques Charles (1746–1823) had discovered this law in 1787, and it is usually known as Charles's law (*see* GAS LAWS), but Charles had not published it.

In 1804, Gay-Lussac and the physicist Jean-Baptiste Biot (1774–1862) were commissioned by the Academy of Sciences to measure the Earth's magnetic field high above the surface. On August 24, they ascended by balloon from the garden of the Conservatoire des Arts and climbed to 13,120 feet (4,000 m). On September 16, Gay-Lussac made a solo ascent in which he reached a height of 23,012 feet (7,019 m) above sea level. This was higher than the tallest peak in the Alps, and it established an altitude record that stood for 50 years. Measurements made during the flights showed not only that the magnetic field remains constant with height, but that the chemical composition of the atmosphere also does so. This discovery makes Gay-Lussac one of the founders of METEOROLOGY. The same year he read a paper describing research on a method of chemical analysis he had done in collaboration with von Humboldt. Using this method, they had found (among a number of other things) that the proportions of the volumes of HYDROGEN and OXYGEN in water were 2:1.

In 1809, Gay-Lussac published what may have been his most important discovery. He had found that when gases combine they do so in simple proportions by volume and that the products of their combination are related to the original volumes. This is known as Gay-Lussac's law and it is used in chemical equations. One of the examples Gay-Lussac used to illustrate it shows that when two molecules of CARBON MONOXIDE (CO) combine with one molecule of oxygen (O_2) the product is two molecules of CARBON DIOXIDE (CO_2):

$$2CO + O_2 \rightarrow 2CO_2$$

From about 1810, Gay-Lussac concentrated increasingly on pure chemistry. He made many important discoveries. These included improving the processes used to manufacture oxalic and sulfuric acids, devising ways to estimate the alkalinity of potash and soda, and the amount of chlorine in bleaching powder. He developed volumetric analysis, and in 1832 he introduced a method for estimating the amount of silver in an alloy by using common salt.

His advice was constantly in demand, and he held a number of official positions. In 1805, he was appointed to the consultative committee on arts and manufactures. In 1818, he was appointed to the department responsible for the manufacture of gunpowder, and in 1829 he became chief assayer to the Mint. Both of these positions were lucrative government appointments.

Joseph Gay-Lussac died in Paris on May 9, 1850.

Hadley, George

(1685–1768)
English
Meteorologist

George Hadley was born in London on February 12, 1685. He studied law and qualified as a barrister (under the English legal system, this is a lawyer who is permitted to appear as an advocate in the higher courts).

Hadley became increasingly interested in physics, however, and in particular in the physics of the atmosphere. He was placed in charge of the meteorological observations that were prepared for the Royal Society, a task he performed for at least seven years.

In 1686, Edmund Halley (1656–1742) had proposed an explanation for the reliability of the trade winds (*see* WIND SYSTEMS). Halley's theory was plausible, but it failed to account for the direction of the trade winds, which blow from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. George Hadley aimed to complete the theory by explaining the direction of the winds. He agreed with Halley that hot air rises over the equator and is replaced by cooler air flowing toward the equator from higher latitudes, but he noted that the Earth itself is rotating in an easterly direction at the same time. Consequently, the moving air is deflected in a westerly direction, resulting in winds that blow in the directions that are observed. Two centuries passed before this deflection was described in detail by Gaspard de Coriolis. It is now known as the CORIOLIS EFFECT. In 1735, Hadley presented his account of the atmospheric movements that produce the trade winds to the Royal Society as a paper titled "Concerning the Cause of the General Trade Winds."

Hadley had produced the first model for the GENERAL CIRCULATION of the atmosphere. This supposed there is one large CONVECTION cell in each hemisphere. Warm air rises over the equator, moves to the pole where it subsides, and then returns to the equator. Although this model explains the easterly component of the trade winds, however, it fails to account for the westerly winds that prevail in middle latitudes. Hadley's mistake was to assume there is just a single convection cell in each hemisphere. In fact, three sets of cells are included in the three-cell model of the atmospheric circulation. Also, meteorologists now know that the Coriolis effect is weak in low latitudes and does not exist at the equator, so it cannot be the full explanation for the direction of the trade winds. William Ferrel (1817–91) discovered the true cause of the deflection in the 19th century.

Despite these failings, George Hadley was one of the first people to develop a credible scientific description of the atmospheric circulation. His paper to the Royal Society aroused little interest at the time, and it was not until 1793, long after his death, that John Dalton (1766–1844) recognized Hadley's importance as a meteorologist. That contribution to METEOROLOGY is acknowledged to this day in the name of the Hadley cells.

George Hadley died at Flitton, Bedfordshire, on June 28, 1768.

Halley, Edmond (Edmund)

(1656–1742)
English
Astronomer

Edmond Halley was born at Haggerston, Shoreditch, which was then a village near London, on October 29 according to the Julian calendar, which was then in use, or on November 8 according to the Gregorian calendar, which is in use today, in the year 1656. He said he was born in the year 1656, but there is some doubt about this, partly because in 17th-century England the year began on March 25, and not January 1 as it does today.

The family was from Derbyshire, in the English Midlands, and Edmund's father, who was also called Edmund, had grown wealthy by making soap at a time when the use of soap was increasing throughout Europe. He was murdered in 1684.

Edmund senior could afford a good education for his son, and after employing a tutor to teach him at home, sent the boy to St. Paul's School. Young Edmund excelled in Latin and Greek and in mathematics, and he displayed a talent for devising and making scientific instruments. In 1673, he entered Queen's College at the University of Oxford, where he wrote a book on the laws of Johannes Kepler (1571–1630). This drew him to the attention of John Flamsteed (1646–1719), the Astronomer Royal.

Halley left Oxford without taking a degree, a practice that was not unusual in those days. Flamsteed employed him as an assistant and then helped him launch his career by spending two years on the island of Saint Helena, charting the stars of the Southern Hemisphere. The project was financed partly by Halley's father and partly by King Charles II. In 1678, after his return from Saint Helena, Halley was elected to the Royal Society.

His reputation grew rapidly. On December 3, 1678, Oxford University awarded him a degree without requiring him to take the examination, and in 1679 the Royal Society sent him to Danzig (now Gdansk) to resolve a disagreement between Robert Hooke (1635–1703) and the German astronomer Johannes Hevelius (1611–87). Hevelius, a close friend of Halley's, had made certain astronomical observations without using telescopic sights, and Hooke claimed that the observations could not be accurate.

Halley became friendly with Isaac Newton (1642–1727) and financed the publication of Newton's major work, *Philosophae Naturalis Principia Mathematica* (Mathematical principles of natural philosophy). Halley's success alienated Flamsteed, who became increasingly hostile toward him.

In about 1695, Halley began making a careful study of the ORBITS of comets. He calculated that the comet that had appeared in 1682 was the same object that had been seen in 1531 and 1607, and in 1705 he predicted that it would be seen again in December 1758. When it appeared on December 25, 1758, it was given his name. It is still known as Halley's comet.

Although astronomy was his principal interest, Halley also studied TIDES, winds, and weather phenomena. In 1686, he attempted an explanation of the trade winds (*see* WIND SYSTEMS) by proposing that air is heated more strongly at the equator than it is elsewhere. The warm air rises and draws in cooler air from higher latitudes, flowing toward the equator.

For a time Halley commanded the *Paramore Pink,* a warship, exploring the coasts on both sides of the Atlantic, charting variations in compass readings, and investigating the tides along the English coast. He also inspected harbors in southern Europe on behalf of Queen Anne.

In 1704, Edmund Halley was appointed Savilian professor of geometry at Oxford, and in 1720, he succeeded Flamsteed as Astronomer Royal. Flamsteed's widow was so angry at this that she arranged for all of her husband's instruments to be removed from the Royal Observatory and sold, to prevent Halley from using them.

Edmund Halley died in Greenwich, London, on January 14, 1742, by the Julian calendar and January 25, 1742, by the Gregorian calendar. His tombstone bears an inscription stating that he died in 1741, but this is also correct, because of the change in the date of New Year's Day.

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Helmont, Jan Baptista van

(1577–1644)
Flemish
Physician and alchemist

Jan van Helmont discovered the existence of gases and claimed to have coined the word *gas*. He also identified the gas we know as CARBON DIOXIDE.

Van Helmont was born in Brussels (his date of birth is not known, but it was in the year 1577), and he was educated at Louvain. He studied several sciences, finally concentrating on medicine, in which he graduated in 1599. In 1609, van Helmont moved to Vilvorde, near Brussels, where he spent the rest of his life practicing medicine and conducting chemical experiments.

In his work and ideas van Helmont bridged the medieval and modern worlds. He was a mystic, interested in the supernatural, and an alchemist who believed in the philosopher's stone—the object alchemists believed would change base metals such as lead into gold. He even claimed to have seen it used. Van Helmont believed in spontaneous generation, by which living organisms develop from nonliving materials, and he asserted that mice are produced from dirty wheat.

At the same time, Jan van Helmont was in touch with the scientific developments of his day, and his experiments were performed carefully and accurately. In one experiment he grew a willow tree in a measured quantity of soil to which he added only water. At the end of five years, he found the tree had gained

164 pounds (74.5 kg) in weight, but the soil had lost only two ounces (57 g). Van Helmont concluded that the tree was converting water into its own tissues. This was incorrect, but it was an early example of a carefully quantified experiment in biology, and it did prove that plants do not draw their principal nourishment from the soil.

Some of his experiments produced vapors, and van Helmont was the first person to recognize that these are distinct substances, each with its own properties. Unlike liquids and solids, vapors immediately fill any space they enter. He thought this meant they existed in a state of chaos, a word he spelled *gas,* which is the way it sounded when spoken by a Flemish speaker.

Charcoal gives off a gas when it is burned, and because the gas comes from wood, for which the Latin word is *silva,* van Helmont called it "gas sylvestre." He discovered that the same gas is given off when malted barley is fermented to make beer. It is the gas we call carbon dioxide.

Jan van Helmont continued experimenting and working as a physician until his death, on December 30, 1644.

Henry, Joseph

(1797–1878)
American
Physicist

As a boy, Joseph Henry showed little interest in school. He was born in Albany, New York, on December 17, 1797. His family was poor, and at 13 Joseph left school and was apprenticed to a watchmaker.

Henry might have remained a watchmaker, but for a curious event that happened when he was 16 and spending a vacation on a farm owned by a relative. A rabbit he was chasing ran beneath a church, and Joseph crawled under the building to follow it. Some of the floorboards above him were missing, so he climbed through the gap and into the church, where he came across a shelf of books. One, called *Lectures on Experimental Philosophy,* attracted him. He started to read it and was inspired to return to school.

Joseph Henry enrolled at Albany Academy to study chemistry, anatomy, and physiology, paying his way by teaching in country schools and tutoring. He graduated, hoping to practice medicine, but in 1825 he obtained a job surveying a route for a new road in New York State. This aroused his interest in engineering, but in 1826 he returned to Albany Academy to teach mathematics and science—which was then known as natural philosophy.

Electricity and magnetism were research topics of great interest in Europe, and Henry began experimenting with electromagnets. He was the first American since Benjamin Franklin to undertake important experimental work with electricity. He was the first person to insulate wire for the magnetic coil, using silk from one of his wife's petticoats, and he invented spool winding. In 1829, Joseph Henry made the first electromagnetic motor, and by 1831 he was able to make a range of electromagnets, from very delicate ones to one that could lift 750 pounds (340 kg) and another that lifted more than one ton.

In 1832, Joseph Henry was appointed a professor at the College of New Jersey (now Princeton University). The same year Henry discovered self-induction—the phenomenon in which an electric current flowing through a wire coil induces a second current in the coil, so the current becomes the original and induced currents combined. Henry had read a preliminary account of work on induction by the British physicist and chemist Michael Faraday (1791–1867). Henry was the first to perform the key experiments, but Faraday was the first to publish his results. Nevertheless, at a meeting in Chicago in 1893, the Congress of Electricians named the henry as the unit of inductance. It is now the SI unit of inductance (*see* UNITS OF MEASUREMENT).

This work gave Henry another idea. Suppose there were a very long wire with a battery at one end, an electromagnet at the other, and a key that would open and close the circuit. Every time the key closed the circuit a current would reach the electromagnet, which would attract a small iron bar, causing it to move. When the key was released, opening the circuit, the attraction would cease and a small spring would pull the iron bar back to its original position. When the iron bar moved, it would make an audible click, so if the key were pressed repeatedly to make a pattern of taps, the same pattern would be heard as clicks from the iron bar. By 1831, Henry had made this device and it was working. He had invented the telegraph, and in 1835 he invented the relay. This was a series of similar circuits in which each circuit activated the next. It overcame the diminution in the signal passing through a length of wire that is caused by resistance in the wire itself.

Joseph Henry believed that scientific discoveries should benefit everyone. He did not patent his inventions, and he was happy to describe them in detail. Consequently, it was Samuel Morse (1791–1872) who made the first practical telegraph line and who patented the telegraph.

In December 1846, Joseph Henry was elected the first secretary of the Smithsonian Institution, which had only recently been founded. An excellent administrator, he turned the institution into a major clearinghouse for scientific information.

Henry mobilized scientific effort during the American Civil War. He was elected the second president of the National Academy of Sciences and was active in organizing the American Association for the Advancement of Science and the Philosophical Society of Washington.

One of his first projects at the Smithsonian reflected another of his interests: METEOROLOGY. Henry established a corps of voluntary observers, located all over the United States, who used the telegraph to send weather reports to a central office at the Smithsonian. This was the first use of the telegraph for a scientific purpose. For the next 30 years, Henry supported and encouraged this volunteer corps. When the UNITED STATES WEATHER BUREAU was established in 1891, it used the system that Henry had devised for collecting data.

Joseph Henry died in Washington on May 13, 1878. His funeral was attended by many government officials and by Rutherford B. Hayes, president of the United States.

Hero of Alexandria

(ca. 60 C.E.)
Greek or Egyptian
Engineer

Hero lived in Alexandria, Egypt, and it is not certain whether he was Egyptian or Greek; there was a flourishing Greek community in Alexandria at that time.

Greek or Egyptian, Hero was a gifted mathematician and teacher. He founded a school, part of which was devoted to research. He was also an inventor. He devised systems of gears for lifting heavy objects, and used a suction machine to raise water. Hero also invented the first steam engine, although it was no more than a novelty and not strong enough to perform useful work. The device consisted of a hollow sphere that was made to spin rapidly by the pressure of steam from boiling water.

Hero demonstrated that air is a substance. He believed it is made from minute particles, and he discovered that it can be compressed. This idea had to wait 1,600 years before being developed by Robert Boyle (1627–91) and his contemporaries.

Hooke, Robert

(1635–1703)
British
Physicist

One of the most ingenious experimenters and instrument makers who have ever lived, Robert Hooke was born on July 18, 1635, at Freshwater, in the Isle of Wight, which is an island off the southern coast of England. His father, John Hooke, was a clergyman, employed as the curate at Freshwater. A curate is an assistant to the parish priest; it is a poorly paid occupation.

John wanted his son to enter the church, but as a child Robert was often ill and he was not strong enough to undertake the necessary studies. He spent much of his time alone, amusing himself by making mechanical toys. Later, he attended school in Oxford, and after the death of his father in 1648 Robert was sent to London. At first he seems to have embarked on an apprenticeship, for which he paid the £100 he inherited from his father. Then he enrolled at Westminster School. He learned Latin and Greek, although he never wrote in either, but his best subject was mathematics, in which he excelled. It took him only a week to master the geometry of Euclid. In 1653, he entered Christ Church College, at the University of Oxford. At first he was a chorister and then he became a servitor. This was an undergraduate student who was assisted financially from the college funds, in return for which he performed certain menial duties. Robert was already a highly skilled instrument maker, and he earned a living by selling ideas for modifications and improvements to the owners of the professional workshops where scientific instruments were made.

He did not take a degree, but while he was at Oxford Hooke joined a group of brilliant scientists, one of whom was Robert Boyle (1627–91). Boyle was a wealthy man and employed Hooke as an assistant, paying him generously. The two became close lifelong friends, and although Hooke ceased to be employed by Boyle in 1662, Boyle continued to pay him until 1664, when Hooke was in a better financial position.

Hooke's first task, in 1658, was to help design a pneumatic pump that would remove air from a vessel into which animals and scientific instruments could be placed and the effect on them observed. Hooke succeeded, and Boyle used the pump for his experiments on gases.

In 1659, the group of friends began to separate. Most of them, including Boyle and Hooke, moved to London where, in 1660, they formed a scientific society. In 1662, this became the Royal Society of London. Hooke was appointed curator of experiments for the society, a position that required him to demonstrate new experiments at each weekly meeting. He was paid £30 a year and was provided with accommodation in Gresham College, in London. In 1663, he was elected a fellow of the society, and in the same year he was awarded an M.A. degree from Oxford. In 1664, he was made a lecturer in mechanics at the Royal Society, for which he received £50 a year, and in 1665 he was appointed professor of geometry at Gresham College, also at a salary of £50 a year. He remained in these two posts for the rest of his life. From 1677 until 1683, he was secretary to the Royal Society.

His work for the society, and especially his job as curator of experiments, involved him in every branch of science and allowed him to develop to the full his mechanical skills. It also meant, however, that although he originated many ideas and improved other people's inventions, he left many projects unfinished.

Despite that, his achievements were considerable. He found that the stress placed on an elastic body is proportional to the strain it produces. This is known as Hooke's law. He invented an anchor escapement mechanism for a watch and claimed it was the first, although that led to a dispute over priority with Christopher Huygens (1629–95). He also claimed to have discovered gravitation and the INVERSE SQUARE LAW before Isaac Newton (1642–1727). He greatly improved the design of microscopes, and his book *Micrographia,* published in 1665, contained the first important set of drawings of microscopic observations. He insisted that fossils were the remains of plants and animals that had lived long ago.

Hooke invented the wheel barometer, which indicated the pressure by means of a needle on a dial, and he suggested ways to apply BAROMETER readings to WEATHER FORECASTING. It was Hooke who first labeled a barometer with the words "change," "rain," "much rain," "stormy," "fair," "set fair," and "very dry." He designed, but did not make, a weather clock to record air TEMPERATURE, PRESSURE, rainfall, HUMIDITY, and WIND SPEED on a rotating drum. He suggested that the freezing point of water be used as the zero reference point on THERMOMETERS.

Hooke died in London on March 3, 1703.

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Howard, Luke

(1772–1864)
English
Chemist, pharmacist, and meteorologist

Luke Howard devised a method for classifying clouds that formed the basis of the system that was adopted internationally and that remains in use to this day. His was not the only attempt at classification, and it was far from being the first. At about the same time as Howard was developing his scheme, the Chevalier de Lamarck (1744–1829) also proposed a scheme (*see* CLOUD CLASSIFICATION) and developed it over several years. Lamarck was a leading scientific figure and an authority on biological classification, but his cloud classification was based on rather vague definitions. Whether for that reason or some other, his scheme was not adopted, and Howard's was.

Luke Howard was born in London into a Quaker family and was educated at a Quaker school at Burford, near Oxford. He was educated as a pharmacist (druggist), and when he grew up he earned his living as a manufacturer of chemicals. He was a businessman and chemist, but he was never a professional scientist.

His interest in METEOROLOGY was kindled in the summer of 1783, when he was 11 years old. That year there were two major volcanic eruptions, one in Iceland and the other in Japan. Volcanic dust formed a haze around the world that produced spectacular skies. Then, on August 18, Luke witnessed a dramatic meteor blaze across the sky. He began to keep a record of his meteorological observations and maintained the habit for more than 30 years.

Howard was a founder member of the Askesian Society, which was one of the many philosophical societies (philosophy was the name given to what we now call science) formed in the late 18th and early 19th centuries. At a meeting of the society in 1800, he presented a paper on "The Average Barometer," and in 1802 he presented another paper on "Theories of Rain."

Howard became interested in biological classification, which was then being strongly influenced by the work of the Swedish naturalist Linnaeus (Carl Linné, 1707–78). In 1735, Linnaeus had published a book, *Systema Naturae,* in which he introduced a system based on a binomial nomenclature, in which every species was given two names, one of its genus and the other of the species itself. In 1803 (although some historians say it was in December 1802), Howard presented a paper to the Askesian Society, "On the Modification of Clouds." He wished to describe the way clouds change from one form to another, but to do so he needed names by which to identify each type. Howard followed Linnaeus in allotting Latin names to cloud types, and he suggested ways of combining the names in a Linnaean, binomial fashion.

Howard proposed that all clouds belong to one of three groups. He called these "cumulus," "stratus," and "cirrus." A fourth group, called "nimbus," denoted a cloud that was producing RAIN, HAIL, or SNOW. *Cumulus,* the Latin word for "heap," Howard described as "convex or conical heaps, increasing upward from a horizontal base—Wool bag clouds." *Stratus,* the past participle of the Latin verb *sternere,* to strew, and meaning "layer," he described as "a widely extended horizontal sheet, increasing from below." *Cirrus,* the Latin word for a "curl," he described as "parallel, flexuous fibers extensible by increase in any or all directions." *Nimbus,* the Latin for "cloud," but to which Howard attached the meaning "rain," he described as "a rain cloud—a cloud or system of clouds from which rain is falling."

Howard maintained that rain could not fall from cumulus, stratus, or cirrus as long as they "retain their primitive forms." Clouds can alter their forms, however. Cumulus clouds could fill the sky to become cumulo-stratus, which is "cirro-stratus blended with cumulus." Similarly, cirrus could become cirro-cumulus and cirro-stratus.

His classification attracted widespread attention, and Howard became a celebrity, his fame increasing even more when all his meteorological papers up to that time were collected by Thomas Forster and published in 1813 as *Researches About Atmospheric Phaenomenae.* Wolfgang von Goethe even dedicated four poems to Howard.

In 1806, Howard began a publication called the *Meteorological Register,* which appeared regularly over several years in the *Athenaeum Magazine.* In 1818–19, he published the first book ever written on urban climate: *The Climate of London,* in two volumes, and in 1833 published as an expanded second edition in three volumes. In it he made what is believed to be the first reference to what is now called a HEAT ISLAND, with temperature records to support it. A heat island is an urban area that is warmer than the surrounding countryside. A series of lectures he delivered in 1817 were published in 1837 as *Seven Lectures in Meteorology* and became the first textbook on the subject. His last book, *Barometrographia,* appeared in 1847.

In recognition of his contributions to meteorology, in 1821 Howard was elected a fellow of the Royal Society of London, the highest honor British scientists can bestow on one of their colleagues.

Luke Howard remained a devout Quaker throughout his life. He died at a great age in London in 1864.

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Humboldt, Friedrich Heinrich Alexander, Baron von

(1769–1859)
German
Geologist, geophysicist, geographer

Alexander von Humboldt was born in Berlin on September 4, 1769. Berlin was then the capital of Prussia, and von Humboldt's father was a Prussian officer who served as an official at the court of the king, Frederick II (Frederick the Great) and who wanted his son to pursue a political career. Alexander was more interested in science, however, and following the death of his father in 1779, he was educated privately before enrolling at the University of Göttingen in 1789 to study science.

While a student at Göttingen, von Humboldt met Georg Forster (1754–94), who had accompanied James Cook (1728–79) on the second of his voyages of exploration. The two became firm friends, and Humboldt spent only one year at Göttingen before he and Forster set off on a journey through the Netherlands and England, where he met many leading scientists.

On his return to Prussia, Humboldt realized he would need a formal qualification if he were to make any useful contribution to science. In 1791, he became a student at the Freiburg Bergakademie (School of Mining). He spent two years there before graduating in geology, and while studying mining he became fascinated by the plants that grow in and around mines.

After graduating from the Bergakademie, Humboldt was appointed assessor of mines and later director of mines in the Prussian principality of Bayreuth. He founded a school of mining, improved conditions for the miners, and also conducted his own research into the magnetic declination of the rocks in the area. He spent the years from 1792 to 1797 on a diplomatic mission that took him to the salt-mining regions of several central European countries. In the course of these travels he met more of the most senior scientists of the day.

Humboldt's mother died in 1796, and Alexander inherited a share of the family fortune. This meant he no longer needed to earn a living and could indulge his passion for travel. He went first to Paris and from there to Marseilles, accompanied by the French botanist Aimé Bonpland (1773–1858). They planned to travel to Egypt, where they hoped to join Napoleon, but instead they went to Madrid, where the prime minister, Mariano de Urquijo, became their patron. With his support they changed their plans and determined to visit the Spanish colonies in South America.

The two friends sailed from Spain in 1799, landed in New Andalusia (modern Venezuela), and early in 1800 they started on a four-month expedition through Latin America. They explored the course of the Orinoco and confirmed that the headwaters of the Orinoco were linked to those of the Amazon. By the time they returned to their base on the coast, at Cumaná, they had traveled 1,725 miles (2,775 km). They then sailed to Cuba and stayed there for several months before returning to South America in March 1801, arriving at Cartagena, Colombia.

They then embarked on a second expedition, this time on a route that crossed the Andes. As they climbed, Humboldt noted the changes in vegetation at different elevations and recorded the decrease in air TEMPERATURE with height. He also made many geophysical observations of the alignment of VOLCANOES and of the Earth's magnetic field. When they reached the Pacific coast, Humboldt measured the temperature of the water offshore and discovered the existence of the cold current that is sometimes named after him, but nowadays more usually known as the Peru Current (*see* APPENDIX VI: OCEAN CURRENTS).

Humboldt and Bonpland left South America in February 1803, spent a year in Mexico, visited the United States, and sailed for Europe on June 30, 1804. In the course of their explorations the two men had covered about 6,000 miles (9,600 km).

Humboldt spent the following years in Berlin and Paris arranging the vast amount of material he had collected during his travels—including 60,000 plant specimens, many of which were new to science—and writing accounts of his experiences and discoveries. His major work, *Voyage de Humboldt et Bonpland,* appeared in 30 volumes between 1805 and 1834. Most of his fortune had now been spent, and in order to secure an income Humboldt agreed to serve as a Prussian diplomat in Paris.

Humboldt was one of the founders of biogeography, the study of the geographic distribution of plants and animals. He was the first scientist to measure the decrease of temperature with altitude, and he investigated the cause of tropical storms. This supplied information other scientists used later to determine the processes involved in the weather systems of middle latitudes.

His many discoveries and his liberal opinions had made Humboldt a celebrity. He was said to be the second most famous man in Europe, after Napoleon. He died in Berlin on May 6, 1859, at the age of 89 and was given a state funeral.

Keeler, James Edward

(1857–1900)
American
Astrophysicist

James Keeler studied the rings of Saturn, the surface of Mars, and nebulae, but he began his career as an assistant to Samuel Pierpont Langley (1834–1906).

Keeler was born at La Salle, Illinois, on September 10, 1857. He did not attend school between the ages of 12 and 20, but during these years he learned as much as he could about astronomy. A wealthy benefactor made it possible for him to enroll at Johns Hopkins University, where he graduated in 1881.

In 1881, Keeler began to work for Langley and accompanied him on the ascent of Mount Whitney, California, to measure the intensity of solar radiation at the summit and compare it with measurements they had made at the base of the mountain. In 1883, Keeler went to Germany to study at the Universities of Heidelberg and Berlin. He returned to the United States in 1884. He was appointed astronomer at the newly built Lick Observatory, on Mount Whitney, in 1888, became director of the Allegheny Observatory in 1891, and in 1898 he returned to the Lick Observatory as its director. Keeler was elected a fellow of the Royal Astronomical Society of London in 1898 and a member of the National Academy of Sciences in 1900.

He died unexpectedly on August 12, 1900, in San Francisco.

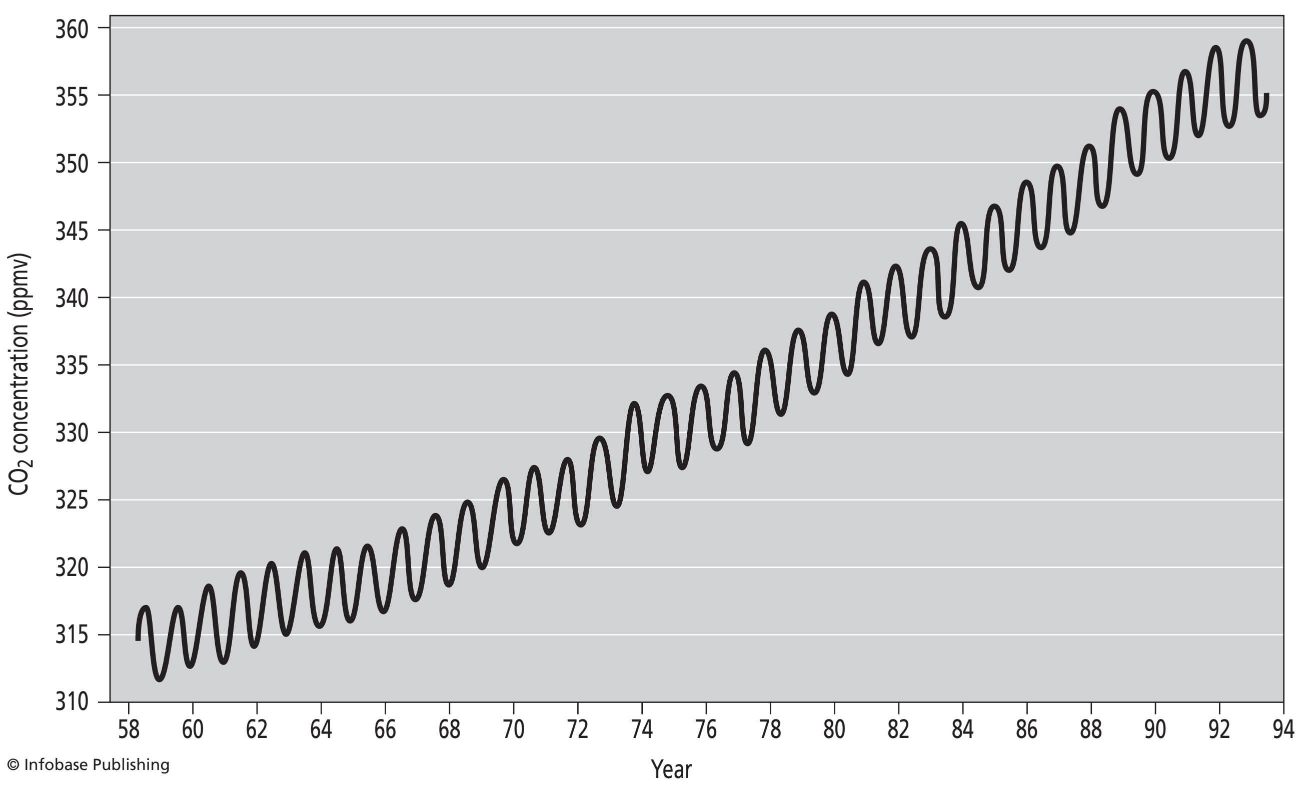
Keeling, Charles David

(1928–2005)
American
Geochemist

Charles Keeling devised a technique for measuring the atmospheric concentration of CARBON DIOXIDE and used it to show that the concentration was rising. Until that time, the idea that the burning of coal and oil might alter the amount of carbon dioxide in the air was largely supposition. Svante Arrhenius and others had shown this was possible, but scientists believed any surplus would dissolve into the oceans and remain there. Keeling's precise monitoring of carbon dioxide levels demonstrated for the first time that carbon dioxide was accumulating in the atmosphere. The present demand to curb carbon dioxide emissions arises very largely from Keeling's work.

Charles Keeling was born at Scranton, Pennsylvania, on April 20, 1928. He studied chemistry and isotope chemistry at the University of Chicago and was awarded his Ph.D. from Midwestern University in 1954.

Roger Revelle, director of the Scripps Institution of Oceanography, of the University of California, San Diego, offered Keeling a job, and in 1956 Keeling moved to the Scripps, where he remained for the rest of his career, moving away only for short secondments. In 1961–62, Keeling was a Guggenheim Fellow at the



The Keeling curve, showing carbon dioxide concentrations at Mauna Loa, Hawaii

Meteorological Institute, University of Stockholm, Sweden; in 1969–70, he was a guest professor at the University of Heidelberg, Germany; and in 1979–80, he was a guest professor at the Physical Institute of the University of Bern, Switzerland.

Revelle and his colleague Hans Suess had realized that the surface water of the oceans mix very slowly with deeper water, thus limiting the capacity of the oceans as a sink for dissolved carbon dioxide. Measuring the atmospheric concentration of carbon dioxide suddenly became important. That is the background against which Keeling developed his technique. There is a widely publicized graph showing the steady rise in atmospheric carbon dioxide measured at the Mauna Loa mountain station in Hawaii. The graph is often called the "Keeling curve."

In 2002, President George W. Bush presented Keeling with the National Medal of Science, America's highest award, for a lifetime achievement in scientific research. Keeling received many other awards, including the 1993 Blue Planet Prize from the Science Council of Japan and the Asahi Foundation, and the 2005 Tyler Prize for Environmental Achievement.

Charles David Keeling died from a heart attack at his home in Montana on June 20, 2005.

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Kepler, Johannes

(1571–1630)
German
Astronomer and mathematician

Johannes Kepler calculated the ORBITS of the solar system planets. His three laws of planetary motion showed that: (1) Planets follow elliptical orbits with the Sun at one of the two foci; (2) A line from the Sun to a planet crosses equal areas of space in equal periods of time; and (3) The square of the orbital period of a planet is proportional to the cube of its mean orbital radius from the Sun.

Kepler had less well known claims to fame. He was the author of the first ever science fiction story. He was also fascinated by SNOWFLAKES.

Kepler was born at Weil der Statt, Württemberg, on December 27, 1571. He attended schools in Weil, Leonberg, and Adelberg before enrolling at the University of Maulbronn, where he graduated in theology in 1588. He moved to the University of Tübingen in 1589 to study philosophy, mathematics, and astronomy, obtaining his master's degree in 1591. In 1594, he was appointed professor of mathematics at the University of Graz.

Those were troubled times. Kepler was a Protestant, and in 1598 a religious purge drove him from Graz. He spent a year in Prague before returning, only to be expelled once more, so he went back to Prague. This time he stayed there, in 1600 becoming an assistant to the aging Danish astronomer Tycho Brahe (1546–1601). His meticulous study of Brahe's voluminous records led Kepler to formulate his laws of planetary motion.

In 1611, Johannes Kepler wrote his science fiction story. *Somnium* was about the adventures of a man who travels to the Moon. The story was not published until 1631, after Kepler's death.

It was also in 1611 that Kepler published a description of snowflakes, called *A New Year's Gift, or On the Six-cornered Snowflake*. He dedicated the book to his patron and friend Matthaüs Wackher.

Johannes Kepler died at Regensburg (then called Ratisbon), Bavaria, on November 15, 1630.

Kirchhoff, Gustav Robert

(1824–1887)
German
Physicist

Gustav Kirchhoff, the physicist who discovered BLACKBODY radiation, was born at Königsberg, Prussia (now Kaliningrad, Russia), on March 12, 1824. He was educated at the University of Königsberg, and in 1854 he became professor of physics at the University of Heidelberg.

At Heidelberg Kirchhoff met Robert Wilhelm Bunsen (1811–99), the inventor of the laboratory burner named for him. Bunsen was a gifted inventor, and he and Kirchhoff collaborated in developing the spectroscope. That instrument allowed them to analyze compounds by the light spectra they emitted when heated with the Bunsen burner.

Gustav Kirchhoff also calculated that a perfect blackbody, absorbing all the radiation falling upon it, would emit radiation at all wavelengths if it were heated to incandescence. The Scottish physicist Balfour Stewart (1828–87) reached the same conclusion independently at about the same time, but Kirchhoff is usually credited with the discovery.

Gustav Kirchhoff died in Berlin on October 17, 1887.

Köppen, Wladimir Peter

(1846–1940)
German
Meteorologist and climatologist

Wladimir Köppen was born in St. Petersburg, Russia, on September 25, 1846. His parents were German, and after attending school in the Crimea, he returned to Germany to study at the Universities of Heidelberg and Leipzig. While he was at school in Russia, Wladimir first became interested in the natural environment and especially in the interaction between plants and climate. His student dissertation, which he completed in 1870, dealt with the relationship between TEMPERATURE and plant growth.

Following his graduation, from 1872 to 1873 he was employed in the Russian meteorological service. In 1875, he returned once more to Germany to take up an appointment as chief of a new division of the Deutsche Seewarte, based in Hamburg. His task there was to establish a WEATHER FORECASTING service covering northwestern Germany and the adjacent sea areas. His primary interest lay in fundamental research, however, and he was able to devote himself to it from 1879, once the meteorological service was functioning.

Köppen embarked on a systematic study of the climate over oceans and also investigated the upper air, using kites and balloons to obtain data. In 1884, he published the first version of his map of climatic zones (*see* KÖPPEN CLIMATE CLASSIFICATION). He plotted these on an imaginary continent he called "Köppen'sche Rübe" ("Köppen's beet"). His CLIMATE CLASSIFICATION appeared in full in 1918, and after several revisions the final version of it was published in 1936.

In addition to writing hundreds of articles and scientific papers, Köppen co-authored with Alfred Wegener (1880–1930) *Die Klimate der Geologischen Vorzeit* (The climates of the geological past), published in 1924, and wrote *Grundriss der Klimakunde* (Outline of climate science), which was published in 1931. In 1927, he entered into collaboration with Rudolf Geiger to produce a five-volume work, *Handbuch der Klimatologie* (Handbook of climatology). This was never completed, but several parts, three of them by Köppen, were published.

Köppen had moved to Graz, Austria, to work on the *Handbuch der Klimatologie,* and it was there that he died, on June 22, 1940.

Lamb, Hubert Horace

(1913–1997)
English
Climatologist

One of the first scientists to draw attention to the variability of climates and the social and economic consequences of climate change, Hubert Lamb was arguably the greatest climatologist of the 20th century. In addition to his studies of climate change and the history of climates, Lamb was among the most skillful of weather forecasters.

Hubert Lamb was born at Bedford and educated at Oundle School, in Northamptonshire, and then at Trinity College, Cambridge, where he studied natural sciences and geography. He graduated in 1935 and received a master's degree in the same subjects in 1947. In 1981, he was awarded honorary doctorates from the Universities of Dundee (LL.D.) and East Anglia (D.Sc.), and in 1982 Cambridge University awarded him a doctorate of science.

In 1936, following his graduation from Cambridge, Lamb went to work at the British METEOROLOGICAL OFFICE. As war became increasingly probable, Lamb was asked to study the way clouds of poison gas would be carried by the wind. He refused to do this on moral grounds, and in 1940 he was transferred to the Irish Meteorological Office. In 1941, he was placed in charge of preparing forecasts for transatlantic flights. His forecasts were so accurate that during his period at the Irish Meteorological Office transatlantic flights out of Ireland had a perfect safety record. Eventually, he had a disagreement with the director, however, and in 1945 he returned to the Meteorological Office in Britain.

Lamb sailed as meteorologist on a Norwegian whaling expedition to Antarctica in 1946–47, and during this voyage he came to realize the extent to which climate changes over time. He served as a weather forecaster in Germany from 1951 to 1952, and from 1952 until 1954 he worked in Malta.

During all of this time, from 1945 until 1971, Hubert Lamb was employed by the Meteorological Office and devoted part of his time to long-range WEATHER FORECASTING and studies of global weather and climate change. In 1954, he was placed in charge of the Climatology Division at the Meteorological Office. While there, he undertook the first detailed study of the past climate records held at the office. He used these to trace ways the climate had changed since the middle of the 18th century and devised a classification system, known as LAMB'S CLASSIFICATION, for British weather.

Hubert Lamb also came to realize that DUST injected high into the air by volcanic eruptions can affect surface weather by reflecting incoming solar radiation back into space, thereby shading the surface. This led him to study every eruption since 1500 and to estimate the amount of dust each had released and its effect on weather in the years following. From this he developed a method for estimating the climatic effect of volcanic dust, known as LAMB'S DUST VEIL INDEX.

In 1971, Lamb left the Meteorological Office to establish the Climatic Research Unit at the University of East Anglia, in Norwich. He remained director of the unit until his retirement in 1977, and after retiring he remained at the university as an emeritus professor. Under his direction the unit became one of the foremost centers for the study of climate change.

Hubert Lamb died in Norwich on June 28, 1997.

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Langley, Samuel Pierpont

(1834–1906)
American
Astronomer and physicist

Using an instrument of his own invention, Langley was the first scientist to calculate the amount of energy the Earth receives from the Sun and the proportion of that energy absorbed by the atmosphere. He was also the first person to explain clearly how birds are able to soar without flapping their wings, and he came very close to inventing the airplane.

Langley was born at Roxbury, Massachusetts, on August 22, 1834. He was educated at Boston Latin School and Boston High School, graduating in 1851, but he did not go to college, so he was largely self-educated. From 1857 until 1864, he worked as a civil engineer and architect, mainly in Chicago and St. Louis. At the same time, he studied astronomy, and by the time he returned to Boston in 1865 he had attained a sufficiently high standard to be offered a post as an assistant at the Harvard University observatory. In 1866, he left to teach mathematics at the U.S. Naval Academy at Annapolis, Maryland, and in 1867 he was appointed director of the Allegheny Observatory in Pennsylvania and professor of physics and astronomy in the Western University of Pennsylvania. In 1887, he became secretary and then director of the Smithsonian Institution, in Washington, D.C., a post he retained until his death. While there, he established the Washington National Zoological Park and the Smithsonian Institution's astrophysical observatory at Wadesboro, North Carolina.

Throughout his life, Langley was fascinated by all solar phenomena and especially by the task of discovering the amount of solar radiation that reaches the Earth and provides the energy to drive the atmospheric and ocean circulations that produce the world's climates. In 1881, he climbed Mount Whitney, California, accompanied by the American astronomer James Edward Keeler (1857–1900). From the summit the two were able to measure the heat of the solar rays and compare this with the value they measured at sea level. The measurements were made with a BOLOMETER, an instrument Langley had invented for the purpose of studying the SOLAR SPECTRUM.

Langley was also interested in the way that air flows across surfaces, and he made a number of experiments that allowed him to calculate the forces operating on a body moving through the air at a constant speed. He showed how thin wings of a certain shape could support the weight of an airplane, and in 1896 he made a steam-powered airplane. It carried no pilot, but it flew across the Potomac River, a distance of 4,200 feet (1,281 m). Between 1897 and 1903, he made three trials, but failed to achieve a successful flight carrying a pilot. The structural materials available to him were not strong enough and his engines were unreliable. These trials cost $50,000, paid from public funds, and after the third failure he was unable to raise more. The *New York Times* published an editorial berating Langley for wasting public money on a foolish dream, predicting that it would be a thousand years before humans achieved powered flight. The Wright brothers made their flight nine days later, on December 17, 1903.

Samuel Pierpont Langley died at Aiken, South Carolina, on February 27, 1906.

Langmuir, Irving

(1881–1957)
American
Physical chemist

A Nobel laureate, Irving Langmuir was the director of the General Electric research laboratory, at Schenectady, New York, where Vincent Schaefer (1906–93) and Bernard Vonnegut (1914–97) performed the first experiments in CLOUD SEEDING.

Irving Langmuir was born in Brooklyn, New York City, on January 31, 1881. He attended local schools and then a boarding school in a Paris suburb, his parents having moved to Paris for three years. The Langmuirs returned to the United States in 1895, moving to Philadelphia. Irving continued his schooling at Chapel Hill Academy and then at the Pratt Institute, in Brooklyn. In 1903, he graduated in metallurgical engineering from the School of Mines at Columbia University. He obtained his Ph.D. at the University of Göttingen, Germany. After a brief spell teaching, Langmuir joined the staff of the General Electric research laboratories, where he remained for the rest of his career.

Langmuir studied the effect of hot metals on gases, work with direct implications for the development of tungsten filament lamps filled with NITROGEN, which did not blacken as "vacuum-filled" lamps did. He also investigated the properties of liquid surfaces, and during World War II he helped develop more effective smokescreens, using SMOKE particles of an optimum size. This work led to the use of solid CARBON DIOXIDE and silver iodide particles for cloud seeding. For his work on surface chemistry, Langmuir received the 1932 Nobel Prize in chemistry.

Irving Langmuir retired in 1950. He died at Falmouth, Massachusetts, on August 16, 1957.

Laplace, Pierre-Simon, Marquis de

(1749–1827)
French
Mathematician and astronomer

A mathematical and scientific genius, Laplace rose rapidly from humble origins to become very famous and influential. He was born on March 28, 1749, at Beaumont-en-Auge, Normandy, where his father owned a small estate. Neighbors who were better off than the Laplace family recognized that the boy had talent and helped to pay for his education. When he was 16, Pierre enrolled at the University of Caen, where his tutors recognized his genius. He graduated in mathematics after two years, and in 1767, aged 18, he traveled to Paris with a letter of introduction to the famous French mathematician Jean le Rond d'Alembert (1717–83). D'Alembert refused to see him, so the young man sent him a paper on mechanics. This was of such high quality that d'Alembert was delighted with it and sponsored Laplace for a professorship. Only 18 years old, Laplace was appointed professor of mathematics at the École Militaire.

Early in his career, Laplace collaborated with the French chemist Antoine Laurent Lavoisier (1743–94) in determining the specific heats of many substances. In 1780, they were able to show that the amount of heat needed to decompose a compound into its constituent elements is equal to the amount that is released when those elements combine to form the compound. This discovery is regarded as the beginning of the branch of chemistry called thermochemistry. It also developed further the work of Joseph Black (1728–99) on LATENT HEAT and pointed the way toward the concept of the conservation of energy. Sixty years later, this was to become the first law of thermodynamics (*see* THERMODYNAMICS, LAWS OF).

Most of Laplace's work was in mathematics and in the mechanics of the solar system. He published this work between 1799 and 1825 in five volumes called *Mécanique Céleste* (Celestial mechanics), for which he is sometimes known as the French Newton. In 1812, Laplace published *Théorie Analytique des Probabilités* (Analytical theory of probabilities), developing this further in *Essai Philosophique* (Philosophical essay), published in 1814. This work gave the theory of probability its modern form and, with it, helped establish statistics as a branch of mathematics.

In 1799, Napoleon appointed Laplace minister of the interior, but dismissed him after only six weeks and promoted him to the rank of senator. Napoleon later made him a count, and when Louis XVIII was restored to the throne in 1814, far from being penalized for his association with Napoleon, Pierre Laplace was promoted again, this time to the rank of marquis.

Laplace was elected to the Academy of Sciences in 1785. In 1816, he was elected to the far more prestigious French Academy, and in 1817 he became its president. He died in Paris on March 5, 1827.

Leverrier, Urbain-Jean-Joseph

(1811–1877)
French
Astronomer

Urbain Leverrier was an authority on many aspects of astronomy and contributed to the discovery of the planet Neptune. He was also instrumental in establishing a network of meteorological observing stations throughout France and in issuing the first daily weather bulletins for French cities.

Urbain Leverrier was born on March 11, 1811, at St. Lô, Normandy. His father, a civil servant, sold his house to pay for Urbain's education. Leverrier attended local schools and then the Collège de Caen from 1828 until 1830. From Normandy he moved to the Collège de St. Louis in Paris, where in 1831 he won a prize in mathematics, which gained him admission to the École Polytechnique. Given a choice of the branch of public service he would enter, Leverrier opted for the Administration Tobaccos, where he conducted chemical research under the guidance of Joseph-Louis Gay-Lussac (1778–1850). Leverrier then began teaching chemistry privately and at the Collège Stanislas, but when in 1837 he applied for a post as a demonstrator at the École Polytechnique, he was offered a position in astronomy, rather than chemistry. He accepted and, almost by accident, became an astronomer.

Leverrier soon came to be recognized as a highly talented astronomer. His studies of Mercury won him election to the Paris Academy of Sciences in 1846, and later that year he discovered Neptune. In 1847, he became a fellow of the Royal Society.

Urbain Leverrier was also active politically. He sided with the Republicans in the 1848 revolution, becoming a member of the legislative assembly in 1849 and a senator in 1852, but Leverrier changed his allegiance later in 1852 when Louis Napoleon came to power and declared himself Napoleon III.

Leverrier was appointed director of the Paris Observatory in 1854. He was an unpopular director, who kept a tight rein on expenditure and the direction of research, and in 1870 he was dismissed. His successor died unexpectedly, however, and Leverrier was reinstated.

On November 14, 1854, during the Crimean War, a fierce storm devastated the Anglo-French fleet near Balaklava, in the Black Sea. The minister for war in Napoleon's government asked Leverrier to study the storm. Leverrier used records from weather observers to reconstruct the track of the storm and was able to demonstrate that if SYNOPTIC WEATHER MAPS had been available and if information had been telegraphed to commanders, the fleet would have had a day to prepare. Leverrier persuaded the government to use the state telegraph service for this purpose, and in 1855 he began to supervise the establishment of a network of observing stations across France. On January 1, 1858, Leverrier launched a daily weather bulletin with observations from 14 French cities and four cities outside France. From September 1863, the daily *Bulletin International de l'Observatoire de Paris* contained a weather map for western Europe, showing isobars (*see* ISO-), pressures, and wind directions.

Leverrier's health deteriorated steadily over a number of years. He died in Paris on September 23, 1877.

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Lorenz, Edward Norton

(b. 1917)
American
Meteorologist

As they develop, weather systems demonstrate chaotic behavior (*see* CHAOS). Edward Lorenz was the scientist who discovered this fact.

Edward Lorenz was born in West Hartford, Connecticut, on May 23, 1917. He was educated at Dartmouth College, Harvard University, and the Massachusetts Institute of Technology (M.I.T.), from where he graduated in mathematics. During World War II, Lorenz served as a weather forecaster in the U.S. Army Air Corps. He continued as a meteorologist after the war, joining the M.I.T. faculty in 1946. He received his doctor of science degree at M.I.T. in 1948. Lorenz was professor of METEOROLOGY at M.I.T. from 1962 until 1981; since then he has been professor emeritus of meteorology.

Lorenz's research centered on ways to improve weather forecasts by programming a computer to track changes in an atmospheric variable, such as TEMPERATURE, over a long period. One day in 1961, he ran his program after he had fed into it the initial conditions printed out from an earlier run of the same program. He expected that the second run would reproduce the results of the earlier run, but to his surprise the weather system described in the second run developed in a markedly different way. On investigating the reason for the difference, Lorenz discovered that in the first run he had entered values with six decimal places, but the printout he used for the second run had rounded these to three decimal places. He had assumed, wrongly, that such a small difference would have no effect.

On December 29, 1979, Lorenz described this result in a paper he presented at the annual meeting of the American Association for the Advancement of Science in Washington, D.C. The title of his paper was: "Predictability: Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?" His discovery was quickly nicknamed the "butterfly effect." In subsequent years, Lorenz continued with his investigation of the mathematical theory of chaos.

Lovelock, James Ephraim

(b. 1919)
English
Atmospheric chemist

James Lovelock achieved fame with his proposal of the GAIA HYPOTHESIS, an idea that was immediately attractive to environmentalists, although scientifically it was controversial. Lovelock was born on July 26, 1919, at Letchworth Garden City, Hertfordshire. His father was a keen gardener, and from him James acquired a deep appreciation of the natural world.

The family was not wealthy, and Lovelock did not move directly from school to university. Instead, he obtained a job in a laboratory. During the day he learned practical laboratory techniques, and in the evenings he attended chemistry classes at night school. In time these gave him the qualifications he needed to become a full-time student. He enrolled at the University of Manchester, graduating in chemistry in 1941.

It was wartime, and as an alternative to military service Lovelock was recruited for war work. He joined the staff at the National Institute for Medical Research (NIMR), in London. After the war, in 1946, he remained with the NIMR and went to work at the Common Cold Research Unit, in Wiltshire, where he remained until 1951, taking part in the (ultimately fruitless) search for a cure for the common cold. He received his Ph.D. in 1948 in medicine, from the London School of Hygiene and Tropical Medicine. In 1959, he received the degree of D.Sc. in biophysics from the University of London.

Still an employee of the NIMR, in 1954 Lovelock was awarded a Rockefeller Traveling Fellowship in Medicine. He spent it at Harvard University Medical School, in Boston, and in 1958 he spent a year working at Yale as a visiting scientist. He resigned from the NIMR in 1961 in order to take up an appointment as professor of chemistry at Baylor University College of Medicine, in Houston, Texas.

In the early 1960s, while living in Texas, Lovelock became a consultant at the Jet Propulsion Laboratory (J.P.L.) of the California Institute of Technology, in Pasadena. He had already helped with some of the instruments that were used to analyze lunar soil, and he was asked to advise on various aspects of instrument design for the team of scientists planning the two Viking expeditions to Mars.

One aim of the Viking expeditions was the search for life on Mars, and although Lovelock was not directly involved in this, he began to speculate about how life on another planet might be detected and recognized. After all, organisms that shared no common ancestor with those living on Earth and that had evolved under radically different conditions might possess no visible feature by which they could be identified as living beings. In discussions with Dian Hitchcock, a philosopher employed to assess the logical consistency of NASA experiments, Lovelock reasoned that any living organism must alter its environment by removing substances (such as food) from it and adding substances (such as body wastes) to it. He thought such changes should be detectable and that the simplest place to look for them would be in the planet's atmosphere. Over the years that followed, this line of reasoning led him to formulate the Gaia hypothesis.

James Lovelock has a talent for devising extremely sensitive instruments. Eventually, he decided it might be possible to earn his living in this way, and in 1964 he became a freelance research scientist. Many of his instruments helped to develop and refine the technique of gas chromatography, and in 1957 Lovelock invented the ELECTRON CAPTURE DETECTOR, which is still one of the most sensitive of all detectors. It revealed the presence of residues of organochlorine insecticides such as DDT throughout the natural environment, a discovery that contributed to the emergence of the popular environmental movement in the late 1960s. Later, the electron capture detector registered the presence of minute concentrations of CFCs (chlorofluorocarbon compounds) in the atmosphere.

Although he has now handed over to younger scientists the task of exploring the implications of the Gaia concept, Lovelock retains a lively interest in environmental science and especially in atmospheric science. He lives in a converted mill in a remote part of southwestern England, surrounded by land he owns and has planted with trees, making it a haven for wildlife.

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Magnus, Olaus

(1490–1557)
Swedish
Priest and naturalist

Olaus Magnus is the Latinized name of Olaf Mansson, the author of a work on natural history that contained the earliest European drawings of ICE CRYSTALS and SNOWFLAKES.

Olaus was born at Linköping, in southern Sweden, in October 1490, where his father, Magnus Peterson, was a prominent citizen. In those days, Swedish people did not have family names. Olaus Magnus meant "Olaus the son of Magnus." He had an elder brother, Johannes Magnus (Johannes, son of Magnus, 1488–1544). Olaus attended a school in Linköping, and then he and Johannes spent nearly seven years traveling together around Europe to complete their education.

From 1518 to 1520, Magnus served as the deputy to the papal vendor of indulgences. Indulgences were printed forms that pardoned people for sins they had committed (or in some cases for sins they had not yet committed, but might). On receipt of the requisite fee, the official vendor filled in the name of the sinner. The sale of indulgences was an important source of church revenue. Magnus was ordained a priest in 1519. He was a vicar in Stockholm in 1520 and dean of Strengnäs Cathedral in 1522.

In 1523, the Swedish king, Gustav I (Vasa), sent Magnus to Rome on a diplomatic mission and from there on other missions to several Dutch and German cities. Finally, in 1528, Olaus reached Poland, where he was to meet Sigismund, the grandson of Gustav Vasa and later king of both Poland and Sweden. The Swedish Reformation took place while Magnus was in Poland. He remained firmly Catholic, however, and was expelled from Poland for this reason. In 1530, he severed his links with the king of Sweden, and his property there was confiscated.

Magnus took refuge in Danzig (now Gdansk) in 1534 and later the same year moved to Italy, where he and Johannes lived together, for the first three years in Venice and then in Rome. Johannes was then archbishop of Sweden. When Johannes died in 1544, the pope appointed Olaus Catholic archbishop of Sweden in his place. Magnus always hoped to return to Sweden in this capacity and wrote to the king repeatedly, asking for permission, but to no avail.

Olaus had a distinguished ecclesiastical career, associating with several of the leading figures of his day. As well as being archbishop of Sweden, he was the director of the religious house of St. Brigitta, in Rome.

He had other interests as well, all of them related to his homeland. Olaus was a skilled cartographer. In 1539, he published, in Venice, his *Carta marina.* This was the first detailed and reasonably accurate map of Scandinavia.

His drawings of ice crystals and snowflakes—things unfamiliar to his friends in Rome—were in his *Historia de gentibus septentrionalibus*. This was published in 1555 and became very popular throughout Europe. There were many editions and translations. The first English translation of it, called *History of the Goths, Swedes and Vandals,* appeared in 1658.

The *Historia* was his very personal account of the history and daily life of the peoples of the north, told with great affection and pride, together with many details of the natural history of northern Europe. It remains one of the most important sources of information about life in Scandinavia in the early 16th century. Magnus based his book on experiences he had gathered between 1518 and 1520, the two years he spent traveling in his capacity of deputy to the vendor of indulgences.

Olaus Magnus died in Rome on August 1, 1557.

Mariotte, Edmé

(ca. 1620–1684)
French
Physicist

Edmé Mariotte was born at Dijon in about 1620 and spent most of his life in or near that city. He was ordained as a priest, but he was also a scientist. It was as a reward for his scientific work that he was appointed prior of the abbey of Saint-Martin-sous-Beaune, near Dijon.

When the French Academy of Sciences was founded in 1666, Mariotte was one of its first members. His interests were wide and he wrote on many scientific topics, including vision (*Nouvelle découvertes touchant la vue* [New discoveries touching on vision], 1668), color (*Traité des couleurs* [Treatise on colors], 1681), plants (*De la végétation des plantes* [On the growth of plants], 1679 and 1696), and others. But his most important work concerned the behavior of fluids. He wrote about freezing (*Expériences sur la congélation de l'eau* [Findings on the freezing of water], 1682) and in 1679 he wrote *De la nature de l'air* (On the nature of air).

In *De la nature de l'air* Mariotte reported his observation that "The diminution of the volume of the air proceeds in proportion to the weights with which it is loaded." This states the relationship between the volume a gas occupies and the pressure under which it is held. It is the law discovered much earlier by Robert Boyle (1627–91), and Mariotte had discovered it quite independently, but Mariotte had noticed something else. He found that air expands when it is heated and contracts when it is cooled, so that the relationship between pressure and volume remains true only so long as the TEMPERATURE remains constant. Boyle had overlooked this. The relationship is known in English-speaking countries as Boyle's law and in French-speaking countries as Mariotte's law. The importance of Mariotte's contribution justifies supporting the French view.

Many of Mariotte's papers were contained in the first volume of the *Histoire et mémoires de l'Académie,* published in 1733. His collected papers were published in the Netherlands in 1717 and again in 1740.

Edmé Mariotte died in Paris on May 12, 1684.

Marum, Martinus van

(1750–1837)
Dutch
Chemist

Martinus van Marum discovered OZONE. He was born on March 20, 1750, at Delft and was educated at the University of Groningen, receiving a doctorate in medicine in 1773. He practiced as a physician in Haarlem from 1776 until 1780.

Van Marum became active in the Society of Dutch Chemists between about 1790 and 1808. From 1804 until his death in 1837, he was secretary of the Dutch Society of Sciences in Haarlem. He was also director of the society's Cabinet of Natural History and librarian of the Teyler Museum.

As a scientist, van Marum had wide interests. He studied plant breeding, geology, paleontology, and a range of chemical topics. He was also interested in AIR POLLUTION and the ventilation of factory buildings. His most important work was on electricity and the construction of electrostatic machines.

In 1785, while passing electrical discharges through OXYGEN, van Marum noted the "odor of electrical matter" and the accelerated oxidation of mercury. The odor he described was that of ozone, although he failed to recognize it as a different form of oxygen.

Van Marum corresponded with many of the leading scientists of his day, including Benjamin Franklin (1706–90), Joseph Priestley (1733–1804), Allesandro Volta (1745–1827), and Antoine-Laurent Lavoisier (1743–94). He died in Haarlem on December 26, 1837.

Marvin, Charles Frederick

(1858–1943)
American
Meteorologist

Charles Marvin was chief of the UNITED STATES WEATHER BUREAU for 21 years. He was born at Putnam, Ohio (now part of Zanesville), on October 7, 1858, and was educated at Ohio State University, from which he graduated in 1883.

The Office of the Chief Signal Officer of the U.S. Army was the predecessor of the U.S. Weather Bureau, and scientists employed there were styled "professors." In 1884, Marvin was appointed a "junior professor," a post he held until the establishment of the Weather Bureau in 1891. He then became a "professor of meteorology." In 1913, acting on the recommendation of the National Academy of Sciences, President Wilson appointed Marvin chief of the Weather Bureau.

Marvin's principal scientific contributions lay in his work on the compilation of HUMIDITY tables and the design, improvement, and standardization of meteorological instruments. Although he developed instruments to measure and record every type of meteorological phenomenon, he was especially fascinated by the rotating cups ANEMOMETER. For a time the Weather Bureau was assigned the task of collecting seismological data, and Marvin designed a seismograph. He was also interested in the application of statistical methods to the solution of meteorological problems.

Charles Marvin retired in 1934. He died after a brief illness on June 5, 1943, in Washington D.C.

Maunder, Edward Walter

(1851–1928)
English
Astronomer

Edward Maunder was the scientist who first identified the period from 1645 to 1715, now known as the MAUNDER MINIMUM, during which the recorded number of SUNSPOTS and auroras (*see* OPTICAL PHENOMENA) was extremely low.

Maunder was born in London on April 12, 1851, the youngest son of a Methodist minister. He was educated at King's College London (since 1900 a part of the University of London, but then an independent institution). Following his graduation, he went to work at a bank in London.

In 1873, a vacancy occurred at the Royal Observatory, Greenwich, London, for a photographic and spectroscopic assistant. This was a position within the British Civil Service, for which there was an entry examination. Maunder passed the examination and was appointed to the position, although he had no formal qualification as an astronomer.

In 1891, another new member joined the staff. Annie Scott Dill Russell (1868–1947), a brilliant graduate from Girton College, Cambridge, arrived as a "lady computer." A "computer" was a person who performed the mathematical calculations—computations—necessary to astronomical research. She and Maunder married and then collaborated in writing many articles about the Sun and popular articles on astronomy.

Maunder was given the job of photographing sunspots and measuring their areas and positions. As he did so, he discovered that the solar latitudes in which sunspots appear varies in a regular fashion during the course of the 11-year sunspot cycle.

While engaged in photographing and measuring sunspots, his attention was drawn to the work of the German astronomer Gustav Spörer (1822–95), who had identified a period from 1400 to 1510, when very few sunspots were seen. This period is now known as the SPÖRER MINIMUM. Maunder began searching through old records at the Royal Observatory to see whether Spörer was correct and whether there were any other such periods. It was this search that led to his discovery of the Maunder minimum.

Edward Maunder was a keen and accurate observer who experimented to discover the smallest object that he could see without the help of a lens. This demonstrated that objects seen on the surface of the Sun or any other distant object in fact must be very large and contain much fine detail that is invisible from Earth. He used this line of reasoning to challenge the existence of channels, or "canals," on Mars, although at that time these were widely accepted as genuine, and his minority opinion was brushed aside.

Similarly, his discovery of the sunspot minimum was overlooked. Other scientists thought he placed too much reliance on old records that, in their view, were likely to be incomplete or inaccurate. The Maunder minimum is now known to be a real phenomenon.

Edward Maunder was made a fellow of the Royal Astronomical Society in 1873. He died at Greenwich on March 21, 1928.

Maury, Matthew Fontaine

(1806–1873)
American
Naval officer, oceanographer, and meteorologist

Matthew Fontaine Maury was born on January 14, 1806, in Spottsylvania County, Virginia, and spent his youth in Tennessee. His elder brother was a naval officer, and Matthew dreamed of following in his footsteps. In 1825, when he was 18 years old, Maury realized his ambition and joined the U.S. Navy as a midshipman. He was assigned to the USS *Vincennes* and embarked on a four-year cruise that took him around the world. This was followed by other extended voyages to Europe and to the western coast of South America.

Maury returned to the United States in 1834. In the same year, he married Ann Hull Herndon, and the couple settled in Fredericksburg. Matthew spent the years from 1834 until 1841 writing descriptions of ocean voyages and works on navigation. He also wrote essays urging naval reforms.

In 1839, Maury was injured in a stagecoach accident and rendered permanently lame. No longer fit for active service, in 1841 he was appointed superintendent of the Depot of Charts and Instruments. He remained in this post until 1861. It should have given him a quiet, easy life with ample leisure, but Maury threw himself into it. By the time he left, he had transformed this obscure department into the United States Naval Observatory and the Hydrographic Office.

Matthew Maury was especially interested in ocean currents and the winds that drive them. He issued specially prepared logbooks to captains in which they were asked to record their observations of winds and currents. He charted the course of the Gulf Stream and described it as “a river in the ocean.” Knowledge of the locations and courses of currents allowed captains to sail with them rather than against them, thus shortening the time their voyages took. In 1850, he charted the depths of the North Atlantic Ocean in order to facilitate the laying of the transatlantic cable.

Maury demonstrated very clearly that the comprehensive study of METEOROLOGY at sea called for international cooperation. He had already achieved international recognition when, in 1853, he was able to play a leading role in organizing a conference on oceanography and meteorology in Brussels, which he attended as the United States representative. Two years later, in 1855, he published *Physical Geography of the Sea,* which was the first textbook in oceanography. Also in 1855, he was promoted to the rank of commander.

When the Civil War broke out in 1861, Maury threw in his lot with the South. He resigned from the navy on April 20, three days after his native Virginia had seceded from the Union. A few days later, he was made a commander in the Confederate States Navy. He became head of coastal, harbor, and river defenses, and he invented an electric torpedo for harbor defense and experimented with electric mines. Because of his international reputation, in 1862 he was sent to England to purchase naval supplies.

At the end of the war Maury went into voluntary exile. He settled for a time in Mexico, where he became commissioner of immigration to the emperor Maximilian and attempted to found a Virginian colony. The emperor abandoned the colonization project in 1866, and Maury moved to England.

By 1868, tempers had cooled, and Maury returned home to take up the post of professor of meteorology at the Virginia Military Institute. He settled in Lexington, where he died on February 1, 1873. His body was buried temporarily in Lexington and then moved to Hollywood Cemetery, Richmond, where it remains.

Maury was completely forgiven for having supported the losing side in the Civil War. There is a Maury Hall at the Naval Academy in Annapolis, Maryland, and in 1930 Maury was elected to the Hall of Fame for Great Americans.

Mie, Gustav

(1868–1957)
German
Physicist

Gustav Mie was the physicist who discovered the way small particles scatter light (*see* SCATTERING). He was born at Rostock, on the coast of the Baltic Sea, on September 29, 1868. He was educated at the gymnasium (high school) in Rostock and went on to study mathematics and geology at the Universities of Rostock and Heidelberg. He obtained his doctorate in 1891 from Heidelberg.

Mie worked for a short time as a teacher at a private school. Then in 1892 he obtained a post as an assistant in the Physics Institute of the Technical University of Karlsruhe. He held this position until 1902, when he was appointed extraordinariat (a special professor) at the University of Greifswald. There, in 1908, Mie wrote his paper on the scattering of light. Mie became a professor at the University of Halle in 1918 and in 1924 at the University of Freiburg.

Gustav Mie died at Freiburg im Bresigau on February 13, 1957.

Milankovitch, Milutin
(1879–1958)
Serbian
Mathematician and climatologist

Milutin Milankovitch was the first person to fully develop an astronomical theory to account for major climatic changes. He was born on May 28, 1879, at Dali, near Osijek, in what was then part of Austria–Hungary. He studied at the Vienna Institute of Technology, graduating in civil engineering in 1902 and with a doctorate in technical sciences in 1904. He worked for a construction company for a short time, and in 1909 he moved to take up the professorship in applied mathematics at the University of Belgrade, where he remained for the rest of his career.

The Balkan Wars of the early 20th century led to World War I, and at the outbreak of war Milankovitch was interned by the Austro–Hungarian army. He was held first at Nezsider but then in Budapest, where his captors permitted him to work in the library of the Hungarian Academy of Sciences. He spent the remainder of his time in captivity studying solar climates and the temperatures of the planets.

Sir John Herschel (1792–1871) was the first of several scientists to suggest a link between changes in climate and in the amount of solar radiation received by the Earth. In 1864, James Croll (1821–90) had suggested that changes in solar radiation trigger ice ages. The idea was fairly vague, however, and Milankovitch determined to test it. Astronomical changes occur with great regularity—think of the accuracy with which solar eclipses can be predicted. This meant that if Milankovitch could identify those factors that alter the amount of radiation Earth receives he would be able to calculate mathematically how they had exerted their influence at various times in the past.

Milankovitch found three cyclical changes that seemed relevant, and he calculated their effects over hundreds of thousands of years. In 1920, he published his results and elaborated on them in subsequent years. Although his theory aroused considerable interest, for a long time there was no firm evidence to support it. Confirmation came in 1976, however. The astronomical changes he identified are now known as the MILANKOVITCH CYCLES, and their influence on the initiation and ending of ice ages is widely accepted.

Milankovitch died in Belgrade on December 12, 1958.

Molina, Mario José
(b. 1943)
Mexican
Atmospheric chemist

Professor Molina was the joint winner of the 1995 Nobel Prize in chemistry, sharing it with Paul Crutzen and F. Sherwood Rowland. The prize was awarded for their work in identifying the threat to the OZONE LAYER from chlorofluorocarbon compounds (CFCS).

Mario Molina was born in Mexico City on March 19, 1943, the son of a lawyer. He was educated at a boarding school in Switzerland and then in Mexico City, where he graduated in 1965 with a degree in chemical engineering from the Universidad Nacional Autonoma de Mexico. In 1967, he obtained a postgraduate degree from the University of Freiburg, Germany, and his Ph.D. from the University of California at Berkeley in 1972, where Sherwood Rowland was one of his supervisors. While at Berkeley Molina met and married Luisa Tan, a fellow graduate student.

Molina held teaching and research posts at the Universidad Nacional Autonoma de Mexico, the University of California at Irvine, and from 1982 to 1989 at the Jet Propulsion Laboratory of the California Institute of Technology, in Pasadena. In 1989, he moved to the Department of Earth, Atmospheric and Planetary Sciences and Department of Chemistry at Massachusetts Institute of Technology. He was named M.I.T. Institute Professor in 1997.

The first warnings about what might happen to the ozone layer appeared in 1970. This attracted scientific attention, and in 1974 Molina and Rowland published a paper in the scientific journal *Nature* describing the results of their studies of the chemistry of CFC compounds. At the time, CFCs were used widely as propellants in spray cans and in refrigerators, freezers, and air conditioners, and in foam plastics. Molina and Rowland calculated that these very stable, and therefore long-lived compounds could cross the tropopause (*see* ATMOSPHERIC STRUCTURE) and that once they were in the stratosphere CFC molecules would be broken apart by their exposure to ultraviolet radiation (*see* SOLAR SPECTRUM). This chemical degradation would release chlorine, which would engage in reactions that depleted OZONE. Other atmospheric scientists received their paper with some skepticism, but in 1985 stratospheric ozone depletion was detected. It was eventually found that CFCs were involved, just as Molina and Rowland had indicated.

More recently, Mario Molina has studied the pollution of the troposphere. In particular, he is keen to find ways to reduce pollution levels in large cities that suffer from traffic congestion, such as his native Mexico City. He serves on many committees, including the President's Committee of Advisors in Science and Technology, the Secretary of Energy Advisory Board, National Research Council Board on Environmental Studies and Toxicology, and on the boards of U.S.–Mexico Foundation of Science and other nonprofit environmental organizations.

Morse, Samuel Finley Breese

(1791–1872)
American
Artist and inventor

The man responsible for building the first telegraph line in the world and devising a code by which telegraph messages could be sent simply, efficiently, and reliably, was born on April 27, 1791, at Charlestown, Massachusetts. Charlestown is now part of Boston. His father, Jedidiah, was a clergyman and geographer. Samuel studied art at Yale University, where he developed a keen interest in painting miniature portraits. He graduated in 1810 and then persuaded his parents to allow him to travel to England to study historical painting. He stayed in England from 1811 until 1815.

After his return, his talent and gift for making friends brought him enough portrait commissions for him to earn a living, but he never became wealthy, and Americans were not impressed by his historical paintings. He settled in New York City, where his reputation grew, and he was one of the founders of the National Academy of Design and its first president, from 1826 to 1845. Morse taught art at the University of the City of New York (now New York University [NYU]) and twice ran unsuccessfully for election as mayor of New York, on an anti-Catholic, anti-immigrant ticket.

Electricity and electromagnetism were just becoming known and aroused great interest. In 1832, while returning from one of his visits to Europe to study art, Morse fell to discussing electrical experiments with Charles Thomas Jackson (1805–80), a fellow passenger on the ship. Various people had suggested the possibility of transmitting messages electrically, and his conversations with Jackson gave Morse the idea to make a device that would do so. Unfortunately, his knowledge of electricity was inadequate to the task, but a university colleague drew his attention to the work of Joseph Henry (1797–1878), whom he met later. Henry had already given the idea of the telegraph considerable thought, and he was unstinting in his help and advice, answering all of Morse's questions.

By about 1835, Morse had made a telegraph that worked. Henry had designed one earlier, but Morse believed his was the first. Then began his real task. Having failed to build a "Morse line" in Europe, he set out to persuade a reluctant Congress to appropriate the $30,000 it would cost to build a telegraph line linking Baltimore and Washington, a distance of 40 miles (64 km). In 1843, he finally succeeded, and the line was built in 1844. Morse used his own code, the MORSE CODE, which he had developed by 1838, to transmit the first message: "What hath God wrought?" Within a few years TELEGRAPHY was being used to transmit meteorological data, a development that led directly to the first weather reports and forecasts.

After the feasibility of a telegraph line had been demonstrated, Morse was caught up in a succession of legal actions brought by his partners and other inventors, including Jackson, who claimed priority for the invention. Eventually, Morse established his patent rights and was rewarded by many European governments. In old age he became a philanthropist. He died in New York on April 2, 1872, and in 1900, when it first opened, Samuel Morse was made a charter member of the Hall of Fame for Great Americans on the campus of New York University.

Neumann, John von

(1903–1957)
Hungarian–American
Mathematician and physicist

John (originally Janos) von Neumann was born in Budapest, Hungary, on December 28, 1903. He was educated privately until the age of 14, when he entered the gymnasium (high school), but he continued to receive extra tuition in mathematics.

Von Neumann left Hungary in 1919 to escape the chaotic conditions that followed the defeat of the Austro-Hungarian Empire in World War I. He studied at the Universities of Berlin (1921–23) and Zürich (1923–25), graduating from Zürich with a degree in chemical engineering. He received a doctorate in mathematics from the University of Budapest in 1926 and then continued his studies at the University of Göttingen, where he worked with Robert Oppenheimer (1904–67). Von Neumann worked as an unpaid lecturer at the University of Berlin from 1927 until 1929. He then moved to the University of Hamburg, and in 1930 he immigrated to the United States. He was appointed a visiting professor at the University of Princeton, and in 1931 he became a full professor of mathematics at the newly established Institute of Advanced Studies at Princeton, where he remained for the rest of his life. Von Neumann later held a number of advisory posts for the U.S. government.

John von Neumann made many contributions to mathematics and theoretical physics. He invented the study of game theory.

In the 1940s, von Neumann became interested in METEOROLOGY and began to study the methods used in numerical WEATHER FORECASTING. He devised a technique for analyzing the stability of those methods, and in 1946 he established the Meteorology Project at Princeton. In April 1950, the group led by von Neumann made the first accurate numerical forecast, using the ENIAC computer.

In 1952, von Neumann designed and supervised the construction of MANIAC-1, which was the first computer that was able to use a flexible stored program. His work at Princeton on MANIAC-1 influenced the design of all the programmable computers that followed, including those used in weather forecasting.

Von Neumann received many honors and awards, including the Medal of Freedom, the Albert Einstein Award, and the Enrico Fermi Award, all of which were presented to him in 1956.

By 1956, von Neumann was already in poor health. He died from cancer in Washington, D.C., on February 8, 1957.

Nusselt, Ernst Kraft Wilhelm
(1882–1957)
German
Engineer

Wilhelm Nusselt was born at Nuremberg, Germany, on November 25, 1882. He studied machinery at the Technical Universities of Berlin-Charlottenburg and Munich, graduating in 1904. Nusselt continued his studies of mathematics and physics at the Laboratory for Technical Physics in Munich and completed his doctoral thesis in 1907, on the conductivity of insulating materials.

Nusselt worked in Dresden from 1907 until 1909, when he qualified for a professorship with his studies of heat and momentum transfer in tubes. He was a professor at the Technical University of Karlsruhe from 1920 until 1925 and at the Technical University of Munich from 1925 until his retirement in 1952.

In 1915, Wilhelm Nusselt published his most important paper, "The Basic Laws of Heat Transfer." This was the paper in which he proposed the dimensionless groups in the theory of heat transfer (*see* NUSSELT NUMBER).

Wilhelm Nusselt died at Munich on September 1, 1957.

Oeschger, Hans
(1927–1998)
Swiss
Physicist

Hans Oeschger was born at Ottenbach, near Zürich, on April 2, 1927. He trained as a nuclear physicist in Zürich and obtained his doctorate in 1955 at the University of Bern. In collaboration with Professor F. G. Houtermans, in 1955 Oeschger built a device to measure very low levels of radioactivity. Known as the Oeschger counter, this instrument was used to date deep water taken from the Pacific Ocean. In 1963, he was promoted to professor at the University of Bern, where he founded the Laboratory for Low Level Counting and Nuclear Geophysics and the Division of Climate and Environmental Physics. He remained the director of the division until his retirement in 1992.

In 1962, Oeschger began studying GLACIER ice and pioneered research into ICE CORES. He and his team developed drilling and analytical techniques that allowed them to trace changes in climate over the last 150,000 years. In 1979, they showed that during the last GLACIAL PERIOD the atmospheric concentration of CARBON DIOXIDE was a little more than half that of the present day and that its rise during the last 1,000 years was due to the burning of fossil fuels. He was deeply concerned that the rise in carbon dioxide levels might trigger an enhanced GREENHOUSE EFFECT. Hans Oeschger was one of the lead authors of the First Report of the INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE.

With his colleagues Chester C. Langway and Willi Dansgaard, Oeschger discovered that the Greenland ice cores contained records of abrupt climate changes, now known as DANSGAARD-OESCHGER EVENTS.

After a long illness, Hans Oeschger died at Bern on December 25, 1998.

Pascal, Blaise

(1623–1662)
French
Mathematician, physicist, and theologian

Blaise Pascal discovered that the atmosphere has an upper limit and that atmospheric pressure decreases with altitude. He was born on June 19, 1623, at Clermont-Ferrand, in the Auvergne region of France, but the family moved to Paris in 1631.

His mother died when Blaise was three, and his father, a mathematician and civil servant, brought up the family and supervised Blaise's education. The boy was soon recognized as a mathematical prodigy. In 1640, not yet 17 years of age, he wrote *Essai pour les coniques,* about the geometry of conic sections, that made René Descartes (1596–1650) envious. Between 1642 and 1644, the young Pascal designed and made a calculating machine, based on cogwheels, to help his father in the many calculations his work required. This machine was the ancestor of the modern cash register, and the computer programming language Pascal is named after its inventor. Pascal made and sold about 50 of them, and several are still in existence.

Pascal learned of and became interested in the work of Evangelista Torricelli (1608–47). He repeated the Torricelli experiment, but using red wine and water instead of mercury. Wine is even less dense than water, so Pascal's barometers had tubes 39 feet (12 m) tall and were fixed to the masts of ships!

Pascal also reasoned that if air has weight, then it must cover the surface of the Earth rather like an ocean, with an upper surface. This implied that the weight of air measured by a BAROMETER must decrease with height, because the greater the height of the instrument above the surface the smaller must be the mass of air weighing down on it from above.

In 1646, he returned from Paris to Clermont-Ferrand to test this idea on the Puy-de-Dôme, an extinct VOLCANO, 4,806 feet (1,465 m) high, not far from the town. Pascal was never physically strong, and by 1646 he suffered from severe indigestion and insomnia. There was no question that he could make the strenuous ascent of the Puy-de-Dôme—the climb is very steep—so he enlisted the help of his brother-in-law, Florin Périer. Périer carried a barometer up the mountain, at intervals recording the pressure it registered. This showed a steady decrease in pressure with increasing height. Similar records were made from a second barometer, left at the foot of the mountain. These showed no change in pressure throughout the day. The experiment confirmed Torricelli's discovery that air has weight. This achievement is recognized in the name of the derived SI unit of pressure or stress, the pascal (*see* UNITS OF MEASUREMENT and APPENDIX VIII: SI UNITS AND CONVERSIONS).

Pascal made many more contributions to science and mathematics before his death, in Paris, probably from meningitis associated with stomach cancer, on August 19, 1662.

Priestley, Joseph

(1733–1804)
English
Chemist

Joseph Priestley is conventionally credited with the discovery of OXYGEN. He was born on March 13, 1733, at Fieldhead, Yorkshire. His mother died when he was seven, and he went to live with an aunt, who was a Calvinist. Priestley was educated at the Dissenting Academy at Daventry, Warwickshire, and in 1758 he became a Presbyterian minister. In 1761, he became a language teacher at Warrington Academy.

On a visit to London in 1766, Priestley met Benjamin Franklin (1706–90), who aroused in him a keen interest in science. From that time Priestley combined his duties as a minister with scientific research. He discovered "nitrous air" (nitric oxide, NO) in 1772 and reduced it to dinitrogen oxide (N_2O). He isolated ammonia gas (NH_3) in the same year, and it was also in 1772 that he found that plants release a gas that is necessary to animals. In 1774, he discovered that the same gas is released when mercurous oxide (HgO) or red lead (Pb_3O_4) are heated. A mouse thrived in this gas and combustible materials burned brightly in it. He also observed that when the gas is mixed with nitric oxide (his "nitrous air") a red gas is formed, in fact nitrogen dioxide (NO_2).

Priestley concluded that he had discovered air from which the fiery principle phlogiston had been removed. Consequently, this air readily accepted phlogiston released by burning substances. He called the gas "dephlogisticated air." In fact, Karl Wilhelm Scheele (1742–86) had discovered the gas in 1772, but failed to publish his discovery.

Priestley visited Paris in 1774, where he met Antoine Lavoisier (1743–94) and told him about dephlogisticated air. It was Lavoisier who gave it the name oxygen.

Joseph Priestley joined the Lunar Society, a group of eminent scientists based in Birmingham. (The society's name refers to the fact that they met only on moonlit nights, to reduce the risk of being attacked on the unlit streets.) Priestley continued to voice his dissenting views and his support for the French Revolution. This made him increasingly unpopular with the British authorities, and in 1794 he immigrated to Northumberland, Pennsylvania. He refused a professorship at the University of Pennsylvania and died at Northumberland on February 6, 1804.

Ramsay, William

(1852–1916)
Scottish
Chemist

William Ramsay was awarded the 1904 Nobel Prize in chemistry in recognition of his discovery of the rare gases ARGON, KRYPTON, NEON, and XENON.

Ramsay was born in Glasgow on October 2, 1852, the son of an engineer and grandson of the founder of the Glasgow Chemical Society. At first, William's interests were in music and languages, and in 1866, when he was only 14 years old, this hugely talented boy entered the University of Glasgow to study arts. In 1868, he became interested in science and went to work in the laboratory of the Glasgow City Analyst, where he learned chemistry. In 1870, Ramsay traveled to Germany, where he carried out research in organic chemistry, gaining his Ph.D. in 1873 at the University of Tübingen.

Ramsay then returned to Glasgow to work as a teaching assistant at Anderson's College (later called the Royal Technical College) and then at the University of Glasgow. In 1880, he was appointed professor of chemistry at University College Bristol (later the University of Bristol) and the following year, 1881, he became the college principal. In 1887, he moved to London to become professor of chemistry at University College, a post he held until his retirement in 1912.

While at University College Ramsay reorganized the out-of-date laboratory. His research centered on problems posed by Lord Rayleigh, concerning the composition of the atmosphere, which appeared to contain minute amounts of an unknown gas. In 1894, Ramsay discovered argon (the name means "inert"). In 1895, he recovered HELIUM from a uranium mineral. In 1898, Ramsay and his colleagues managed to obtain 26 pints (15 liters) of argon from liquid air. When they allowed the liquid argon to boil, they found it was mixed with other inert gases. The first to be identified they called neon ("new"). It was lighter than argon, but when the argon had completely vaporized, two gases remained that were heavier than argon. One they called krypton ("hidden") and the other xenon ("stranger").

William Ramsay had many talents. As a young man he was athletic. He was also an expert glassblower and made most of his own laboratory glassware.

Ramsay was knighted in 1902. After his retirement in 1912, he moved to High Wycombe, Buckinghamshire, a small town to the north of London, where he continued to conduct research in converted stables. He died at High Wycombe on July 23, 1916.

Rankine, William John Macquorn

(1820–1872)
Scottish
Engineer and physicist

Rankine devoted most of his working life to studying the principles underlying the operation of engines, especially steam engines. He was born in Edinburgh on July 5, 1820. His father was an engineer, and William trained as a civil engineer. In 1855, he was appointed professor of civil engineering and mechanics at the University of Glasgow, a position he continued to hold until his death. In 1853, he was elected a member, and later a fellow, of the Royal Society.

From his work on engines, Rankine's research led him to more abstract studies of thermodynamics. Lord Kelvin (William Thomson, 1824–1907), Rudolf Clausius (1822–88), and Rankine all discovered at about the same time that heat can be converted to work, and work to heat. In the course of his work on thermodynamics, Rankine devised a TEMPERATURE SCALE that is sometimes used (though not by scientists) as an alternative to the Kelvin scale.

William Rankine died at Glasgow on December 24, 1872.

Raoult, François-Marie

(1830–1901)
French
Physical chemist

The author of RAOULT'S LAW was born at Fournes-en-Weppes, in the Nord département of France, on May 10, 1830. He obtained his doctorate at the University of Paris in 1863 and held a post at the University of Sens before moving to a faculty position at the University of Grenoble, where he remained for the rest of his life.

Raoult was one of the founders of physical chemistry, together with Jacobus Henricus Van't Hoff (1852–1911), Friedrich Wilhelm Ostwald (1853–1932), and Svante Arrhenius (1859–1927). His studies of solutions led him to propound the law for which he is famous.

François-Marie Raoult died at Grenoble, in the département of Isère, on April 1, 1901.

Rayleigh, Lord

(John William Strutt)
(1842–1919)
English
Physicist

The scientist who explained, in 1871, why the sky is blue (*see* RAYLEIGH SCATTERING) spent much of his life studying the properties of light and sound waves, waves in water, and earthquake waves, but his interests were much wider. His most famous discovery was in the field of chemistry, not physics. Rayleigh had become interested in the densities of different gases and found that when he measured the DENSITY of NITROGEN in air it was always 0.5 percent greater than the density of that gas obtained from any other source. He eliminated all the reasons he could think of for this, but the disparity remained, and in desperation in 1892 he published a short note in the scientific journal *Nature* asking for suggestions. He received a reply from the Scottish chemist William Ramsay (1852–1916) who solved the problem in 1894 by discovering the previously unknown gas ARGON. For their discovery, in 1904 Rayleigh was awarded the Nobel Prize in physics and Ramsay received the Nobel Prize in chemistry.

Rayleigh was born as John William Strutt at Terling Place, Langford Grove, Essex, on November 12, 1842. He was educated by a private tutor until he entered Trinity College, Cambridge in 1861, graduating in mathematics in 1865. He then visited the United States, returning to England in 1868 and establishing a private laboratory at his home, Terling Place.

In 1873, when Strutt was 31, his father died and he acceded to the title, becoming the third Baron Rayleigh. Lord Rayleigh, the name by which he is usually known, continued with his research, an occupation that was considered somewhat eccentric for an English aristocrat. Rayleigh was elected a fellow of the Royal Society in the same year he acceded to his title, and in 1879 he succeeded James Clerk Maxwell (1831–79) as Cavendish Professor of Experimental Physics at Cambridge University. After 1884, Rayleigh spent most of his time working in his private laboratory. He held the post of professor of natural philosophy at the Royal Institution, London, from 1887 until 1905, but this allowed him to remain at home for most of the time. Rayleigh was secretary to the Royal Society from 1885 until 1896 and its president from 1905 until 1908. From 1908, until his death, he was chancellor of Cambridge University.

Lord Rayleigh died at Terling Place on June 30, 1919.

Réaumur, René-Antoine-Ferchault de

(1683–1757)
French
Physicist

As well as making a THERMOMETER and devising a TEMPERATURE SCALE with which to calibrate it, Réaumur contributed to many branches of science and technology. His most important work concerned the process of digestion.

Réaumur was born at La Rochelle, in Charente-Maritime on the French Atlantic coast, on February 28, 1683. In 1703, when he was 20, he moved to Paris, where he lived under the protection of a relative who was an important civil servant. Réaumur was admitted to the Academy of Sciences in 1708, on the strength of some mathematical work. In 1710, the authorities commissioned him to prepare a report describing all of the nation's useful arts and manufactures.

His own achievements are considerable. Réaumur invented a kind of white glass that is still known as Réaumur porcelain. He showed that certain curious stones found in southern France were in fact the fossil teeth of animals that are now extinct. He helped devise new methods of steel manufacture, wrote a six-volume work on insects, and was the first person to show that corals are animals. His work on digestion resolved a long-standing debate as to whether food is digested chemically or physically, by being ground up in some way. Réaumur showed experimentally that the process is chemical. He developed his thermometer in about 1730, apparently unaware of the work of Daniel Fahrenheit (1686–1736).

René Réaumur spent much of his time at La Bermondière, his country house in Maine et Loire, where he died on October 17, 1757.

Renaldini, Carlo

(1615–1698)
Italian
Physicist

An aristocrat from Ancona, on the Adriatic coast of northern Italy, Renaldini became professor of philosophy at the University of Pisà. He was also a member of the Accademia del Cimento (Academy of Experiments), in Florence. The Accademia was the principal institution studying the atmosphere.

In 1694, Renaldini proposed a method for calibrating THERMOMETERS. This was causing difficulty, because when heated from freezing to boiling temperature water does not expand at a constant rate and there seemed no reason to suppose that any other liquid would do so. It was agreed that the freezing and boiling temperatures of water should mark two ends of the temperature scale, and Renaldini suggested that the intermediate points might be identified by mixing boiling and ice-cold water in varying proportions. Equal weights of water at 32°F (0°C) and 212°F (100°C) would reveal the point at which to mark the halfway point, 122°F (50°C). Twenty parts of boiling water mixed with 80 parts of freezing water would indicate 68°F (20°C) and so on, with each degree rise in temperature corresponding to the addition of the same amount of heat. The method proved difficult to put into practice and did not overcome the difficulty of depending on the behavior of a particular liquid.

Reynolds, Osborne

(1842–1912)
English
Physicist and engineer

Osborne Reynolds was born on August 23, 1842, in Belfast, Northern Ireland. His father was a mathematician who became a schoolteacher at Dedham Grammar School, in Suffolk, England. This necessitated the family moving to England, but in a sense the family was returning home. Osborne's great-grandfather and great-great grandfather had both held the position of rector in the parish of Debach-with-Boulge, to the northeast of Ipswich, only a few miles from Dedham. Later, Osborne's father also became rector there.

Reynolds began his education at Dedham Grammar School. A proficient mathematician, he left school at 19 and went to work for an engineering company, where he was able to apply his knowledge of mathematics. Having gained some practical experience, Reynolds enrolled at Queens' College, Cambridge, to study mathematics. He graduated in 1867 and was immediately awarded a fellowship at Queens'. He then moved to London to work for John Lawson, a civil engineer, but left in 1868 because he had been elected the first professor of engineering at Owens College, Manchester (now the University of Manchester). Reynolds was elected a fellow of the Royal Society in 1877 and received the Society's Royal Medal in 1888. This was followed by many more medals and honorary degrees.

Reynolds conducted research into the movements of comets and atmospheric phenomena caused by electricity, but his most important work concerned the flow of water through channels, including wave and tidal movements in rivers and estuaries. His discoveries led to his formulation of what is now known as the REYNOLDS NUMBER. The Reynolds number is widely used by meteorologists and atmospheric physicists in calculations of the TURBULENT FLOW of air. Account must be taken of turbulence when designing buildings, aircraft, or any other objects that move through the air or that the air moves around. Turbulence also affects the rate at which atmospheric pollutants disperse.

Reynolds retired in 1905 and died at Watchet, Somerset, on February 21, 1912.

Richardson, Lewis Fry
(1881–1953)
English
Mathematician and meteorologist

In 1922, a book was published with the title *Weather Prediction by Numerical Process*. It described a system for numerical WEATHER FORECASTING, which is the preparation of weather forecasts by the use of mathematical techniques for solving equations. Lewis Fry Richardson, its author, had been developing the system since 1913, and his book contained a worked example to show how it might be done.

Unfortunately, Richardson was half a century ahead of his time. His book demonstrated the principle of numerical forecasting, but some of his equations were incorrect, and the data he used for his example were inaccurate. Only 750 copies of the book were printed, and 30 years later not all of them had been sold. Accurate WEATHER FORECASTING requires detailed information about conditions in the upper atmosphere. Modern meteorologists have access to these data, but they were not available in the 1920s. Nor did Richardson and his contemporaries have access to modern computers or even pocket calculators. His scheme involved so many calculations, all of which had to be performed with paper and pencil, that by the time they were completed the conditions they were forecasting would have come and gone.

Richardson estimated that 64,000 individuals equipped with slide rules would be needed. He imagined them seated in a vast hall, each person dealing with data from a particular WEATHER STATION and everyone occupying a place corresponding to the location of the stations, so the hall was a kind of map of the world. The operation would be coordinated by a person standing at a higher level and pointing a red light at any station that was running ahead of the field and a blue light at a station that was behind. His estimate was very conservative. To produce a forecast for the whole world, the hall would have had to contain more than 200,000 workers, and even so the forecasting would have been able to do no more than keep up with the weather as it developed. If the forecast was to advance five times faster than the weather, more than 1 million workers would have been required.

Had it been possible to produce them fast enough, the forecasts would not have been very reliable. The equations Richardson used work only under certain atmospheric conditions, a fact of which he was unaware. These deficiencies made the method impractical, and so little attention was paid to it. Today, upper-air data and adequate computing power are available. Richardson's book was republished in 1965, and this time it sold thousands of copies. A modified version of his method is now used for making large-scale, long-range weather forecasts.

Lewis Fry Richardson was born into a family of tanners on October 11, 1881, at Newcastle-upon-Tyne, an industrial city in the northeast of England. It was a Quaker family, and Richardson remained a committed Quaker throughout his life. He was educated at a school in York and then studied natural science (physics, mathematics, chemistry, biology, and zoology) at King's College, at the University of Cambridge. In 1927, at the age of 47, he was awarded a doctorate in mathematical psychology by the University of London. (Mathematical psychology is the name given to any theoretical work that uses mathematical methods, formal logic, or computer simulation.)

From 1903 to 1904, Richardson worked for the National Physical Laboratory, a government research institution, and in 1912, following the sinking of the *Titanic,* he conducted experiments with echo-sounding. In 1913, he went to work at the METEOROLOGICAL OFFICE.

Richardson's mathematical work, concerned mainly with the calculus of finite differences, showed great originality. Later in life, he even sought to use mathematics to identify and clarify the causes of war, an interest that arose from his religious beliefs.

During the First World War, Richardson served among fellow Quakers in the Friends Ambulance Unit. He was sent to France, where he tried to practice Esperanto, another interest of his, on German prisoners of war. After the war he returned to the Meteorological Office. It was while serving in France that Richardson worked out the equations needed to forecast the weather. His notes were lost in the chaos of war, but were found later beneath a pile of coal.

As a member of the Society of Friends, Richardson was a pacifist, and in 1920 he resigned from the Meteorological Office when it was absorbed into the Air Ministry. He became head of the Physics Department at Westminster Training College, and in 1929 he was appointed principal of Paisley Technical College (now the University of Paisley) in Scotland. He remained at Paisley until his retirement in 1940.

Retirement gave him time to develop his ideas on eradicating sources of conflict. His two books on the subject, *Arms and Insecurity* and *Statistics of Deadly Quarrels* were published posthumously in 1960, attracting interest among religious and pacifist groups.

During his lifetime, Richardson was best known for his studies of atmospheric turbulence. This led to his proposal of what came to be called the Richardson number (*see* TURBULENT FLOW) for predicting whether turbulence would increase or decrease.

In 1926, Richardson was elected a fellow of the Royal Society of London. He died at Kilmun, Argyll, Scotland, on September 30, 1953.

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Römer, Ole (or Olaus) Christiansen

(1644–1710)
Danish
Astronomer

Ole (sometimes spelled Olaus) Römer was born at Århus, in Jutland, Denmark, on September 25, 1644. He was educated at the University of Copenhagen. In 1671, the French astronomer Jean Picard (1620–82) visited Denmark to ascertain the precise location of Tycho Brahe's observatory. Picard hired Römer as an assistant and when the project was complete took him back with him to Paris. Römer worked as an assistant at the French Academy of Sciences and within a year had been elected a full member.

Römer observed the movements of the satellites of Jupiter. He noted that Jupiter eclipsed the satellites earlier when Jupiter and Earth were approaching each other and later when the two planets were moving apart. He deduced from this that light must travel at a finite speed, contradicting most scientists of his day, who believed light propagated instantaneously. Römer calculated the speed of light, announcing this at a meeting of the academy in 1676 as 141,060 miles per second (227,000 km/s). The true speed is 186,291 miles per second (299,792 km/s), but Römer had made an impressive first attempt at it.

Römer visited England in 1679, where he met Isaac Newton (1642–1727) and Edmund Halley (1656–1742). In 1681, King Christian V recalled him to Denmark, where Römer was appointed astronomer royal and professor of astronomy at the University of Copenhagen. In 1705, he became mayor of Copenhagen.

As well as his astronomical skills, Ole Römer was highly practical and had a talent for making scientific instruments. In about 1701, he made a THERMOMETER and devised a method for calibrating it. Daniel Fahrenheit (1686–1736) met Römer during his visit to Copenhagen in 1708, and the two instrument makers discussed Römer's thermometer. This discussion strongly influenced Fahrenheit in the design of his own thermometer.

Ole Römer died at Copenhagen on September 23, 1710.

Rossby, Carl-Gustav Arvid

(1898–1957)
Swedish-American
Meteorologist

Carl-Gustav Rossby was born in Stockholm, Sweden, on December 28, 1898. He was educated at the University of Stockholm, and in 1918, after graduating with a degree in theoretical mechanics, he moved to the Bergen Geophysical Institute. There he worked with Vilhelm Bjerknes (1862–1951) on oceanographic as well as meteorological problems. When Bjerknes moved to Germany in 1921 to take up a position at the University of Leipzig, Rossby followed him and spent a year there. In 1922, Rossby returned to Stockholm to join the Swedish Meteorological Hydrologic Service.

During the next three years, Rossby traveled as the meteorologist on several oceanographic expeditions. He also studied mathematics at the University of Stockholm, graduating in 1925 with a licentiate. This is a European degree one rank below a doctorate.

In 1926, Rossby visited the United States with a scholarship from the Scandinavian–American Foundation. He joined the staff of the UNITED STATES WEATHER BUREAU in Washington, D.C. At the time this was the only meteorological center in the United States. While working there, Rossby wrote several papers on turbulence in the atmosphere and on the dynamics of the stratosphere (*see* ATMOSPHERIC STRUCTURE).

In 1927, Rossby moved to California. Sponsored by the Daniel Guggenheim Fund for the Promotion of Aeronautics, Rossby established experimentally the first weather service that was designed expressly for the benefit of aviators. It became the model on which later aviation weather services were based.

The following year Rossby received his first important academic appointment when he was made the country's first professor of METEOROLOGY, at the Massachusetts Institute of Technology (M.I.T.). He devised the first university meteorological program, and during the 11 years he spent at M.I.T. he continued to pursue his research interests in the thermodynamics of AIR MASSES, turbulence in the atmosphere and oceans, and on BOUNDARY LAYERS. Later, he became increasingly interested in large-scale atmospheric movements.

In 1939, Rossby was appointed assistant chief of research and education at the U.S. Weather Bureau, but he left in 1940 to become chairman of the Institute of Meteorology at the University of Chicago. Soon after his arrival in Chicago Rossby developed his theory describing the long atmospheric waves that now bear his name (*see* ROSSBY WAVES).

During World War II, Rossby organized training for military meteorologists, while continuing his research on long waves. His wartime work took him to many parts of the world and brought him into personal contact with many British as well as American meteorologists. After the war, he was able to bring many of these scientists to the University of Chicago, where together they played an important part in developing the mathematics needed to introduce numerical WEATHER FORECASTING using electronic computers.

In 1947, Rossby was invited to establish a department of meteorology at the University of Stockholm. This was funded by American and Swedish foundations as well as by international bodies including UNESCO, and it attracted students from many countries. Appropriately, the institute was called the International Institute of Meteorology. Rossby divided his time between working at the institute in Stockholm and at the outpost of the University of Chicago that was opened at the Woods Hole Oceanographic Institute. His work at Stockholm was concerned mainly with the development of numerical forecasting methods for European weather services.

Rossby died in Stockholm on August 19, 1957.

Rowland, Frank Sherwood

(b. 1927)
American
Chemist

F. Sherwood Rowland shared the 1995 Nobel Prize in chemistry with Mario Molina and Paul Crutzen. The prize was awarded to these three scientists for having shown first that the amount of OZONE in the OZONE LAYER might decrease as a result of reactions with chemicals released by human activity, and later that CFCs (chlorofluorocarbons) were the chemical compounds primarily involved.

F. Sherwood Rowland was born on June 28, 1927, in Delaware, Ohio, where his parents had moved the previous year when his father took up the post of professor of mathematics at the Ohio Wesleyan University in that city. As a small boy, Sherwood developed a keen interest in naval history.

He was educated at schools in Delaware, and in 1943 he enrolled at the Ohio Wesleyan University, studying chemistry, physics, and mathematics, but in June 1945, before completing his course, Rowland enlisted in the navy. He was discharged 14 months later in California, hitchhiked the 2,000 miles (3,200 km) back to Delaware, and resumed his studies. These were combined with sport, an interest that began when he was in high school. He played tennis, basketball, and baseball for university teams.

Rowland graduated in 1948 and the same year entered graduate school in the chemistry department at the University of Chicago. He obtained his Ph.D. in 1952, and in June of that year he married Joan Lundberg, a fellow graduate student.

In September 1952, Rowland became an instructor in the chemistry department at Princeton University, where he remained until 1956. He spent three summers, 1953–55, working on the use of tracer chemicals in the chemistry department of the Brookhaven National Laboratory. From 1956 until 1964, he was an assistant professor at the University of Kansas, and in 1964 he was appointed professor of chemistry at the University of California, Irvine, where he is now Donald Bren Research Professor of Chemistry and Earth

System Science. His link with Brookhaven continued until 1994.

In January 1972, Rowland attended a workshop on chemistry and METEOROLOGY in Fort Lauderdale, Florida, where he heard the English chemist James Lovelock describe how he had detected minute concentrations of a CFC in the air. Lovelock thought their great chemical stability would make CFCs useful for tracing the movement of AIR MASSES, but Rowland realized that no molecule can remain inert for ever. At high altitudes it will be broken apart by sunlight. He began to wonder what would happen to CFCs when they decayed. In 1973, Mario Molina joined his group as a research associate, and the two men set about studying the fate of airborne CFC molecules.

Paul Crutzen had already drawn attention to the possibility of depleting stratospheric ozone. Rowland and Molina published the results of their research as a paper in *Nature* in 1974. They had calculated that the breakdown of CFC molecules would release chlorine in a form that would destroy ozone molecules. Their paper stimulated a federal investigation of the situation, and in 1978 the use of CFCs as propellants in spray cans was banned in the United States. The phasing out of the use of CFCs was agreed internationally in 1987 under the terms of the Montreal Protocol on Substances That Deplete the Ozone Layer (*see* APPENDIX IV: LAWS, REGULATIONS, AND INTERNATIONAL AGREEMENTS). It was for this work that Rowland, Molina, and Crutzen were awarded their Nobel Prize.

Rutherford, Daniel
(1749–1819)
Scottish
Chemist

Daniel Rutherford, the chemist who discovered NITROGEN, was born in Edinburgh on November 3, 1749. He studied medicine at the University of Edinburgh, where one of his teachers was Joseph Black (1728–99).

In 1772, for his final thesis, Black set Rutherford the task of examining the portion of air that will not support combustion. Rutherford kept a mouse in an airtight container until the mouse died. Then he burned a candle and some phosphorus in the same air until they would no longer burn. He assumed that the air contained some CARBON DIOXIDE from respiration and burning the candle, so he passed the gas through a strongly alkaline solution to remove the carbon dioxide.

The remaining gas was still noxious. A mouse could not survive in it, and it would not support combustion. Rutherford believed in the phlogiston theory. This proposed that phlogiston, a substance present in all combustible materials, was released when the material burned. Consequently, Rutherford believed the air in the container had accepted all the phlogiston it could hold. He called it "phlogisticated air." Joseph Priestley (1733–1804) and Karl Wilhelm Scheele (1742–86) also discovered the gas at about the same time. In 1790, the French chemist Jean-Antoine Chaptal (1756–1832) gave it the name nitrogen.

Daniel Rutherford became professor of botany at the University of Edinburgh in 1786. He died in Edinburgh on November 15, 1819.

Saussure, Horace-Bénédict de
(1740–1799)
Swiss
Physicist

Horace-Bénédict de Saussure was born at Conches, near Geneva, Switzerland, on February 17, 1740. His education began in 1746, when he enrolled at the public school in Geneva. He entered the Geneva Academy in 1754 and graduated in 1759, having presented a dissertation on the physics of fire. He was then 19 years old.

It was in the following year that he paid his first visit to Chamonix, a small resort in southeastern France standing at the foot of Mont Blanc. This is the tallest mountain in Europe, its peak 15,771 feet (4,810 m) above sea level, and when de Saussure visited it in 1760, no one had ever managed to climb it. De Saussure was fascinated by the mountain and toured the neighboring parishes offering a considerable reward to anyone who discovered a practicable route to the summit. In fact, Mont Blanc was first climbed 26 years later, on August 8, 1786, by Jacques Balmat and Gabriel Paccard. De Saussure climbed it himself in the summer of 1787, reaching the summit at 11 A.M. on August 3, accompanied by a number of guides and his personal valet.

De Saussure returned to the mountain many times over the succeeding years. His interest was not primarily in mountaineering as a sport, but in alpine plants, geology, and METEOROLOGY. From 1773, he began to spend increasing amounts of time in the area and climbed many of the mountains. The first volume of his most famous book, *Voyages dans les Alpes* (Journeys in the Alps) was published in 1779. The remaining three volumes were published between then and 1796. In them he described seven of his alpine journeys.

In 1761, de Saussure applied unsuccessfully for the vacant professorship of mathematics at the Geneva Academy. The following year he applied again, this time for the professorship of philosophy, and was successful. The new professor delivered his inaugural lecture in October. In 1772, he was elected a fellow of the Royal Society of London, and in the same year he founded the Society for the Advancement of the Arts in Geneva.

By this time de Saussure's reputation as a physicist was well established. He is credited with having constructed the first solar collector in 1767. This was a box with a glass top and heavily insulated sides, and he used it to discover why it is always cooler in the mountains than it is at lower levels. He took his box to the top of Mont Cramont. There the outside TEMPERATURE was 43°F (6°C), but the temperature inside the box rose to 190°F (88°C). Then he repeated the experiment 4,852 feet (1,480 m) lower down, on the Plains of Cournier. The air temperature there was 77°F (25°C), but the temperature inside the box was almost the same as it had been at the higher elevation. De Saussure concluded that the Sun shines just as warmly in the mountains as it does on the plains, but that the more transparent mountain air is unable to trap and hold so much warmth.

In 1783, de Saussure invented the hair HYGROMETER, based on his observation that human hairs increase in length as the HUMIDITY rises and grow shorter as the air becomes drier. Hair hygrometers are still the most widely used instruments for measuring relative humidity.

De Saussure married Albertine Boissier in May 1765. In February 1768, in the company of his wife and sister-in-law, he visited Paris, the Netherlands, and England, returning to Geneva in January 1769. In 1771, he visited Italy and in the autumn of 1772, with his wife and six-year-old daughter, he toured Italy, visiting Sicily, climbing Mount Etna, and calling at Rome, Rimini, and Venice before returning to Switzerland over the Brenner Pass. He also had an audience with Pope Clement XIV.

These were turbulent times in Geneva, and de Saussure became involved in politics. He drew up plans in 1776 for the reform of city institutions, and during the troubles of 1782 he was arrested and spent two days in prison. During revolutionary riots in July of the same year, he was besieged in his home for several days, suspected of harboring armed men and concealing weapons. The Terror that began in France after the Revolution of 1789 spread to Geneva, and in 1792 Geneva had its own revolution aimed at introducing a measure of democracy. The following year de Saussure was a member of the commission appointed to draft a constitution for the city. This led to an invitation, which he refused, to stand as a candidate for the governing council. The new constitution failed, and in 1794 the Terror returned.

In 1787, de Saussure resigned from his position at the Geneva Academy, and he then spent some time in the south of France, where he could live at sea level and collect measurements of atmospheric pressure that he could compare with those he had taken in the Alps. His health had begun to deteriorate in 1772, and by 1794 de Saussure was a sick man. He was also experiencing financial difficulties and was compelled to return with his family to the country house at Conches, where he had been born. News of his poverty spread, and he received offers of help from abroad. Thomas Jefferson himself considered offering de Saussure a position at the newly founded University of Virginia. It was not to be. De Saussure remained at Conches, and died there on the morning of January 22, 1799.

Schaefer, Vincent Joseph

(1906–1993)
American
Physicist

Vincent Schaefer was born at Schenectady, New York, on July 4, 1906. After leaving school, he worked for a time in the machine shop at the General Electric Corporation (G.E.C.) in Schenectady. Then, thinking outdoor work would suit him better, he attended classes at Union College, New York, and enrolled at the Davey Institute of Tree Surgery, from where he graduated in 1928 and became a tree surgeon. He was a keen skier and loved the snow, but unable to earn an adequate salary at tree surgery, had to abandon this profession.

In 1933, Schaefer returned to G.E.C. There he came to the notice of Irving Langmuir (1881–1957). In 1932, Langmuir had become the first American industrial scientist to win the Nobel Prize in chemistry. He was at the peak of his fame, and he recruited Schaefer as a research assistant. Schaefer became a research associate in 1938, and he remained at G.E.C. until 1954.

During World War II, Langmuir and Schaefer studied the problem of icing on the wings and other external surfaces of aircraft. This was extremely dangerous and caused many aircraft to crash, but before remedies could be found the scientists had to discover what was causing ice to form.

Working with his colleague Bernard Vonnegut (1914–97), Schaefer studied the formation of ICE and SNOW using a refrigerated box with an inside TEMPERATURE that remained at a constant -9°F (-23°C). He hoped to be able to induce WATER VAPOR to be deposited as ice around DUST particles. This work continued for some years until July 1946, when there was a spell of unusually hot weather. It became difficult to maintain the temperature inside the box, so on July 13 Schaefer dropped some dry ice (solid CARBON DIOXIDE) into the box to chill the air. The result was dramatic. The moment the dry ice entered the air in the box, water vapor turned into ICE CRYSTALS and there was a miniature snowstorm.

This suggested a way to make PRECIPITATION fall from a cloud that otherwise would not have released it. By November 13, Schaefer was ready for a full-scale trial. An airplane flew him above a cloud at Pittsfield, Massachusetts, about 50 miles (30 km) southeast of Schenectady. Schaefer dropped about 6 pounds (2.7 kg) of dry ice into the cloud and started the first artificially-induced snowstorm in history. This discovery led to the development of other techniques for CLOUD SEEDING.

Schaefer received the degree of doctor of science (Sc.D.) in 1948 from the University of Notre Dame, and in 1959 he joined the faculty of the State University of New York at Albany, where he founded the Atmospheric Sciences Research Center. He was appointed professor of atmospheric science at the State University of New York in 1964 and held the position until 1976. He was appointed a fellow of the American Academy of Arts and Sciences in 1957, and in 1976 he received a special citation from the American Meteorological Society.

Schaefer died at Schenectady on July 25, 1993.

Scheele, Karl (or Carl) Wilhelm

(1742–1786)
Swedish
Chemist

Karl Scheele discovered the elements OXYGEN, chlorine, and NITROGEN, as well as a long list of compounds. He was born at Stralsund, Pomerania, on December 9, 1742. Pomerania is now part of Germany, but then it belonged to Sweden. Scheele spoke and wrote in German, however.

Karl was the seventh of the 11 children of a poor family. Until he was 14 he received little education, but then he was apprenticed to an apothecary (druggist) in the city of Göteborg. He was a keen observer, and, determined to learn chemistry, he read and performed experiments. His growing skill and experience allowed him to advance to increasingly prestigious positions as an apothecary in Malmö (1765), Stockholm (1768), and Uppsala (1770). Other Swedish scientists, including Johann Gahn (1745–1818) and Torbern Bergman (1735–84), recognized his talent and helped build his reputation.

In 1775, Scheele was elected to the Swedish Royal Academy of Sciences, and in the same year he moved to Köping, in Västmanland. He remained in Köping for the rest of his life, practicing as an apothecary. He refused offers of academic appointments in England and Germany, and of an invitation to become court chemist to Frederick II of Prussia.

As well as chlorine, oxygen, and nitrogen, Karl Scheele discovered a long list of chemical compounds, yet not one of his discoveries was fully attributed to him. In some cases other scientists genuinely preceded him, and in other cases he failed to complete the research, allowing others to claim the credit. He also made mistakes. When he discovered chlorine, he thought it was an oxygen compound. Nevertheless, Scheele was arguably the greatest chemist of the 18th century.

Scheele had a habit of tasting the substances he discovered. One of these was hydrogen cyanide. This dangerous habit, together with overwork, may have contributed to the decline in his health that began in early middle age. He married while on his deathbed, and died at Köping on May 21, 1786, aged 43.

Schönbein, Christian Friedrich

(1799–1868)
German-Swiss
Chemist

Christian Schönbein, the chemist who discovered OZONE, was born at Metzingen, Württemberg, Germany, on October 18, 1799. He was educated at the Universities of Tübingen and Erlangen, and in 1828 he joined the faculty of the University of Basel, Switzerland. He became a professor at Basel in 1828.

In 1840, Schönbein began to experiment with the peculiar odor that for about half a century people had been noticing in the vicinity of electrical equipment. Schönbein found that he could produce the same smell by allowing phosphorus to oxidize and by electrolyzing water. He traced the smell to a gas that he called ozone, from the Greek *ozon,* meaning "smell."

Christian Schönbein also discovered guncotton—by accident. It seems that he was strictly forbidden to experiment in the kitchen at home, but one day in 1845 his wife was out and he was feeling brave. Working with a mixture of sulfuric and nitric acids, he accidentally spilled some and panicked, grabbing the nearest piece of cloth to mop up the acid before it could do any damage. The cloth happened to be his wife's apron, and he hung it by the kitchen stove to dry. When it was thoroughly dry, the apron disappeared with a pop. Schönbein realized something significant had happened, and when he analyzed the process, he found that the acid had added nitro groups (NO_2) to the cellulose in the cotton to form nitrocellulose, which he found was highly flammable, burning with no smoke and leaving no residue.

Schönbein died at Sauersberg, Baden, Germany, on August 29, 1868.

Schwabe, Heinrich Samuel

(1789–1875)
German
Astronomer and chemist

Heinrich Schwabe, who discovered the SUNSPOT cycle, was born at Dessau, to the southwest of Berlin, on October 25, 1789. His father was a doctor, and his mother ran a pharmacy. Heinrich was educated in Berlin, and at the age of 17 he entered the pharmacy business. After three years he returned to Berlin to study pharmacy at the university. His course lasted two years, and when it ended, in 1812, Schwabe returned to the pharmacy.

While at the university, Schwabe became keenly interested in astronomy and chose a research topic he could pursue during the daytime, during quiet periods in the pharmacy. He thought he might be able to discover a new planet orbiting the Sun inside the orbit of Mercury. Such a planet would be visible as it crossed in front of the Sun's disc. He began observing the Sun in about 1825, using a 2-inch (5-cm) telescope, and what he saw were sunspots. He became fascinated by the appearance and disappearance of the sunspots, and eventually he forgot about the search for a new planet and began drawing the sunspots. This became his life's work. Every day when the sky was clear he would record the sunspots.

In 1829, Schwabe sold the pharmacy and became a full-time astronomer. In 1831, he drew a picture of Jupiter that showed the Great Red Spot for the first time. In 1843, while recognizing the limitations of his equipment, Schwabe was able to announce that the number of sunspots waxes and wanes over a 10-year cycle (in fact the cycle is 11 years). The announcement was ignored, however, until Alexander von Humboldt (1769–1859) referred to it in his book *Kosmos.*

By the end of his life, Heinrich Schwabe had published 109 scientific papers, and the data he had collected filled 31 volumes, which were presented to the Royal Astronomical Society after his death. The Royal Astronomical Society presented him with its gold medal in 1857, and in 1868 he became a fellow of the Royal Society.

Schwabe died at Dessau on April 11, 1875.

Shackleton, Nicholas

(1937–2006)
English
Paleoclimatologist

Sir Nicholas Shackleton was one of the founders of paleoclimatology (*see* CLIMATOLOGY). He pioneered the interpretation of OXYGEN isotope ratios and confirmed that major climate changes were caused by variations in the Earth's solar ORBIT, thus validating the MILANKOVITCH CYCLES.

Nicholas Shackleton was born on June 23, 1937. He studied physics at Clare College, University of Cambridge, graduating in 1961. He received his Ph.D. from Cambridge in 1967 for a thesis entitled "The measurement of palaeotemperatures in the Quaternary era." From 1972 until 1987, he was assistant director of research at the sub-department of QUATERNARY research at the University of Cambridge, and from 1988 he was director of the sub-department. Shackleton was a visiting research fellow at the Lamont–Doherty Geological Observatory of Columbia University 1974–75 and a senior research associate 1975–2004. He was the director of the Godwin Institute of Quaternary Research at Cambridge from 1995 until his retirement in 2004. He was appointed to the academic rank of professor at Cambridge in 1991, and on his retirement he became an emeritus professor.

Shackleton discovered that the OXYGEN isotope ratios found in marine organisms are controlled not by temperature, as had previously been thought, but by the preferential removal of the lighter ^{16}O isotope by EVAPORATION and its accumulation in ICE SHEETS. This made it possible to measure the change in the volume of ice between GLACIAL PERIODS and INTERGLACIALS, while other scientists were able to convert the isotope ratios to temperatures. This work led to the CLIMATE LONG-RANGE INVESTIGATION MAPPING AND PREDICTION (CLIMAP) project. Arising from this work, in 1973 Shackleton found the link between variations in ice volume and the Milankovitch cycles. Shackleton also studied changes in carbon isotopes in order to understand the cause of variations in the amount of CARBON DIOXIDE stored in ICE CORES between glacial and interglacial periods.

As well as his climatological research, Professor Shackleton was a keen clarinet player and an authority on the history of the instrument. He taught a course at Cambridge on the physics of music.

Nicholas Shackleton received many awards and honors. He became a fellow of the Royal Society in 1985, a fellow of the American Geophysical Union in 1990, and a foreign associate of the National Academy of Sciences in 2000. He was awarded the Crafoord Prize by the Royal Swedish Academy of Science in 1995, the Ewing Medal by the American Geophysical Union in 2002, the Royal Medal by the Royal Society in 2003, and the Founder's Medal by the Royal Geographical Society in 2005. He received a knighthood in 1998.

Professor Sir Nicholas Shackleton died on January 24, 2006.

Further Reading

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Shaw, William Napier

(1854–1945)
English
Meteorologist

Shaw contributed greatly to the establishment of METEOROLOGY as a scientific discipline. He was born in Birmingham on March 4, 1854, and educated at a school in Birmingham at Emmanuel College, University of Cambridge, from which he graduated in 1876. He was elected a fellow of the Emmanuel College in 1877 and appointed a lecturer in experimental physics at the Cavendish Laboratory, which is part of the university. In 1898, he was appointed assistant director of the Cavendish Laboratory, but he resigned in 1900 to take up an appointment as secretary of the Meteorological Council. He was made director of the METEOROLOGICAL OFFICE in 1905 and remained there until his retirement in 1920. Shaw was also a reader in meteorology at the Royal College of Science of the Imperial College of Science and Technology, in London, from 1907 until 1920, and from 1920 until 1924 he was the college's first professor of meteorology.

Shaw introduced the millibar (*see* UNITS OF MEASUREMENT), in 1909, as a convenient unit of atmospheric pressure. It was adopted internationally in 1929. Some time about 1915, Shaw devised the TEPHIGRAM. He pioneered the use of instruments carried beneath kites and balloons to study the upper atmosphere and wrote several books on WEATHER FORECASTING, as well as one, *The Smoke Problem of Great Cities* (1925), on AIR POLLUTION. He received many honors, including the

1910 Symons Gold Medal of the Royal Meteorological Society, and in 1915, he received a knighthood.

Shaw died in London on March 23, 1945.

Simpson, George Clark

(1878–1965)
English
Meteorologist

Simpson studied atmospheric electricity and the effect of radiation on polar ice. He also standardized the wind speeds in the BEAUFORT WIND SCALE.

George Simpson was born in Derby on September 2, 1878, the son of a prominent tradesman. He went to school in Derby, leaving in 1894 to work in his father's business, but his reading of popular books about science aroused his interest, and he began attending night school. His father persuaded him to continue his education at Owens College, Manchester. He was coached for the entrance examination, entered the college, and graduated in 1900. He became an unsalaried tutor at Owens College until he won a traveling scholarship in 1902. This allowed him to continue his studies at Göttingen University, in Germany. He then visited Lapland to study atmospheric electricity.

On his return to his college in 1905, which by then had become the University of Manchester, he was appointed to head a newly formed METEOROLOGY department. He was the first lecturer in meteorology at any British university. Also in 1905 Simpson was appointed assistant director of the METEOROLOGICAL OFFICE. He was its director from 1920 until he retired in 1938.

Simpson traveled widely. He spent some time in India inspecting meteorological stations, and in 1910 he traveled as meteorologist on Robert Scott's last expedition to Antarctica. Between 1916 and 1920, he worked in the Middle East and Egypt.

George Simpson assigned wind speeds to the Beaufort scale based on measurements made by an ANEMOMETER standing 36 feet (11 m) above the ground (the international standard is now 20 feet [6 m] elevation). He studied the effect of increasing solar radiation on the polar ice caps, concluding that initially this increases PRECIPITATION, causing the ICE to advance, but that further radiation causes the ice to retreat. As solar radiation decreases, more precipitation falls as SNOW, producing a second advance of the ice.

On the outbreak of World War II in 1939, he came out of retirement, studying electrical storms, and retired for a second time in 1947.

Simpson was awarded the Symons Gold Medal of the Royal Meteorological Society in 1930. In 1935, he was knighted. He died in Bristol on January 1, 1965.

Spörer, Friedrich Wilhelm Gustav

(1822–1895)
German
Solar astronomer

Gustav Spörer identified a period of low SUNSPOT activity that now bears his name. Spörer was born in Berlin on October 23, 1822. He studied mathematics and astronomy at the University of Berlin. After graduating, he worked as a schoolteacher.

Spörer began his solar observations in 1858 and quickly established his reputation. He joined the staff of the Potsdam Astrophysical Laboratory in 1874, and in 1882 he was appointed its chief observer. By 1887, his studies of sunspot activity had convinced him that during the 17th century there had been a period during which there were very few sunspots. He also found a similar lack of sunspots between 1400 and 1510. This is the SPÖRER MINIMUM, which coincided with a sequence of very cold winters.

Gustav Spörer retired in 1894 and died at Potsdam on July 7, 1895.

Stefan, Josef

(1835–1893)
Austrian
Physicist

Josef Stefan discovered the relationship between the TEMPERATURE of a body and the amount of radiation it emits. Ludwig Boltzmann (1844–1906) explained the underlying theory, and the result is now known as the STEFAN-BOLTZMANN LAW.

Josef Stefan was born at St. Peter, a village near Klagenfurt, on March 24, 1835. He attended the gymnasium (high school) at Klagenfurt and enrolled at the University of Vienna in 1853. After graduating, he became a lecturer at the university in 1858, and in 1863 he was appointed professor of higher mathematics and physics. Stefan held this post for the rest of his life. From 1866, he was also director of the Institute for Experimental Physics, and from 1885 he was vice president of the Imperial Academy of Sciences.

Stefan discovered his radiation law in 1879. Isaac Newton (1642–1727) had maintained that the rate at which a body cools is proportional to the difference in temperature between the body and its surroundings. Physicists had known for some time, however, that this was not true if the temperature difference is very large. John Tyndall (1820–93) had measured the radiant heat emitted by a platinum wire heated to several high temperatures, and Stefan followed up this work. Eventually, he found that the radiation emitted by a hot body is proportional to the fourth power of its absolute temperature. In 1884, Boltzmann showed that this could be deduced from thermodynamic principles.

Josef Stefan died in Vienna on January 7, 1893.

Stevin, Simon

(1548–1620)
Flemish
Mathematician

In 1586, Simon Stevin published a book, *Statics and Hydrostatics,* in which he reported his discovery that the pressure a liquid exerts on the surface beneath it depends only on the area of the surface on which it presses and the height to which the liquid extends above the surface. Contrary to what seemed obvious to most people at the time, it has nothing whatever to do with the shape of the vessel holding the liquid. This finding paved the way for Evangelista Torricelli (1608–47), who found a way to weigh air and in doing so invented the BAROMETER.

Stevin, often known by the Latin version of his name as Stevinus, was born in Bruges in 1548. He worked as a clerk in Antwerp and then entered the service of the Dutch government, becoming director for the department of roads and waterways and later quartermaster-general to the Dutch army. He devised for military purposes a scheme for opening sluices in the dikes protecting the polders—cultivated land reclaimed from the sea. This would flood the land in the path of any invading army. He also invented a carriage propelled by sails that ran along the beach and could carry 26 passengers, and he is said to have dropped two objects of different weights from a tall tower and found they reached the ground simultaneously—an experiment usually attributed to Galileo (1564–1642). Stevin established the use of decimal notation in mathematics—representing ½ as 0.5, for example, and ¼ as 0.25. He maintained that decimal weights, measures, and coinage would eventually be introduced.

Stevin wrote in Flemish and advised all scientists to describe their work using their own native language. This was unusual, and his works were all translated into Latin later.

Simon Stevin died either at The Hague or Leiden, two cities in the Netherlands that are 10 miles (16 km) from each other.

Stewart, Balfour

(1828–1887)
Scottish
Physicist

Balfour Stewart discovered the properties of BLACKBODIES independently of Gustav Robert Kirchhoff (1824–87), who was more famous and who is usually credited as the sole discoverer. Stewart is best known, however, for his studies of the Earth's magnetic field.

Balfour Stewart was born in Edinburgh on November 1, 1828. He was educated at the Universities of Dundee and Edinburgh, and after graduating he joined the staff of the Kew Observatory, near London, becoming its director in 1859. In 1870, he joined the faculty of Owens College, Manchester (later the University of Manchester).

Stewart studied the theory of heat exchange and found that if the TEMPERATURE of a body remains constant, the amount of radiation the body absorbs is equal to the amount it emits. His studies of magnetism led him to suggest in 1882 that the daily variations in the orientation of the Earth's magnetic field might be caused by electric currents flowing horizontally in the upper atmosphere. Most of his colleagues thought the idea absurd, but it was confirmed in 1902 by the British-American electrical engineer Arthur Edwin Kenneally (1861–1939) and the English physicist and electrical engineer Oliver Heaviside (1850–1925). They proposed the existence of a layer of the atmosphere that was known for a time as the Kenneally–Heaviside layer and is now called the ionosphere (*see* ATMOSPHERIC STRUCTURE).

Balfour Stewart died near Drogheda, Ireland, on December 19, 1887.

Stokes, George Gabriel

(1819–1903)
Irish
Physicist

One of the most eminent physicists of his generation, George Stokes was born at Skreen, Sligo, Ireland, on August 13, 1819. He went to school in Dublin and to a college in Bristol, England, before enrolling at the University of Cambridge to study mathematics. He graduated in 1841 and became a fellow of Pembroke College.

In 1849, Stokes was appointed Lucasian Professor of Mathematics at the University of Cambridge, a position he held until his death. He was elected secretary of the Royal Society in 1854 and in 1885 its president. The last individual to hold all three of these posts was Isaac Newton (1642–1727).

It was between 1845 and 1850, while working on the theory of viscous fluids, that Stokes developed the law bearing his name. STOKE'S LAW relates the force required to move a body through a fluid to the size and VELOCITY of the body and the VISCOSITY of the fluid. This makes it possible to calculate the FRICTION on a moving body and the TERMINAL VELOCITY of a body falling through the air. It explains why clouds float in the sky, but it can also predict the resistance a ship will experience as it moves through the water.

Stokes also studied sound, light, and fluorescence. He was the first person to show that quartz is transparent to ultraviolet radiation (*see* SOLAR SPECTRUM) but glass is not.

Stokes received a knighthood in 1889. He died at Cambridge on February 1, 1903.

Teisserenc de Bort, Léon-Philippe

(1855–1913)
French
Meteorologist

The scientist who discovered the stratosphere (*see* ATMOSPHERIC STRUCTURE) was born in Paris on November 5, 1855, the son of an engineer. His career began in 1880 when he went to work in the meteorological department of the Central Bureau of Meteorology, in Paris. He undertook three expeditions to North Africa, in 1883, 1885, and 1887, to study the geology and geomagnetism. During the same period, he was growing increasingly interested in the distribution of atmospheric pressure at an altitude of about 13,000 feet (4,000 m).

In 1892, Teisserenc de Bort was made chief meteorologist at the bureau, but he resigned in 1896 in order to establish a private meteorological observatory. This was located at Trappes, near Versailles, and Teisserenc de Bort used it primarily to study clouds and the upper air. He was one of the pioneers in the use of balloons to take soundings of the upper atmosphere, and he described their use and the results he had obtained with them in a paper he published in 1898 in the journal *Comptes Rendus*. As well as working from his own observatory, Teisserenc de Bort conducted investigations in Sweden, over the Zuider Zee and Mediterranean Sea, and over the tropical Atlantic.

The balloon soundings Teisserenc de Bort made revealed that the air temperature decreased with height as expected, but only to an altitude of about 7 miles (11 km). Above this height, the temperature remained constant as far as the greatest altitude his balloons could reach. In 1900, he proposed that the atmosphere comprises two layers. He called the lower layer, in which temperature decreases with height and the air is constantly moving, the troposphere. The Greek word *tropos* means "turning." He found that the upper boundary of the troposphere is marked by a layer he called the tropopause.

Above the tropopause there is an isothermal layer. Teisserenc de Bort believed that because the temperature in this layer remains constant, there is no mechanism such as CONVECTION to make the air move vertically. Consequently, he thought the air might separate into its constituent gases, which would then form layers, with the heaviest gases at the bottom and the lightest at the top. Immediately above the tropopause there would be a layer of OXYGEN, above that a layer of NITROGEN, then HELIUM, and a layer of HYDROGEN at the top. This stratified arrangement led him to name the isothermal layer the stratosphere. The stratosphere is not, in fact, layered in the way Teisserenc de Bort supposed, but his name for it has survived.

Teisserenc de Bort died at Cannes on January 2, 1913.

Theophrastus

(371 or 370–288 or 287 B.C.E.)
Greek
Philosopher

Theophrastus is often called the "father of botany" for his studies of plants and attempts at plant classification.

His interests embraced the entire field of contemporary knowledge, however, and they included atmospheric phenomena. Two of his books, *On Weather Signs* and *On Winds* are among the earliest accounts of natural signs and their meteorological significance (*see* WEATHER LORE).

Theophrastus was the nickname Aristotle (384–322 B.C.E.) gave him; it means "divine speech." He was born Tyrtamus in 371 or 370 B.C.E. at Eresus on the island of Lesbos. His education began in Lesbos, and as a young man he went to Athens to study at the Academy headed by Plato (428 or 427–348 or 347 B.C.E.), where Aristotle also taught. Aristotle left Athens soon after Plato died, and Theophrastus may have accompanied him. When Aristotle returned to Athens in 335 B.C.E., Theophrastus continued studying under him at the Lyceum.

Aristotle retired to Chalcis in 322 or 321 B.C.E., appointing Theophrastus as his successor and bequeathing him his library. Theophrastus built a covered walkway, in Greek a *peripatos,* at the Lyceum, and his style of philosophy, based mainly on Aristotelian teaching, became known as the Peripatetic School. He was the most successful of all the peripatetic philosophers. At one time he had 2,000 students. His popularity is attested by the fact that an attempt to charge him with the capital offence of impiety collapsed.

Theophrastus presided over the Peripatetic School for 35 years, until his death in 288 or 287 B.C.E. He was honored with a public funeral, and many Athenians followed the funeral procession to his grave.

Thornthwaite, Charles Warren

(1899–1963)
American
Climatologist

C. W. Thornthwaite was one of the most eminent climatologists of his generation, with an international reputation. He held many important positions, but his enduring fame rests on the CLIMATE CLASSIFICATION he devised. This remains in widespread use, especially among agricultural scientists, because of its emphasis on thermal efficiency and PRECIPITATION efficiency, two concepts that Thornthwaite introduced.

Major climate classifications do not appear all at once, in their complete and final form. Their authors revise and amend them over the years, and Thornthwaite was no exception. The first version of his scheme applied only to North America. It appeared in October 1931, in an article titled "The Climates of North America According to a New Classification" that appeared in the *Geographical Review* (21: 633–55). He expanded the classification to cover the world in another article, "The Climates of the Earth," that appeared in the *Geographical Review* in July 1933 (23:433–40). In January 1948, he published a second version of his classification, in which he introduced the concept of potential EVAPOTRANSPIRATION. He described the new scheme in a third article, "An Approach Toward a Rational Classification of Climate" (*Geographical Review* 38:55–94).

Charles Warren Thornthwaite was born on March 7, 1899, near Pinconning, in Bay County, Michigan. He graduated as a science teacher in 1922 from Central Michigan Normal School and received his doctorate from the University of California, Berkeley, in 1929. Thornthwaite held faculty positions from 1927 to 1934 at the University of Oklahoma, from 1940 to 1946 at the University of Maryland, and from 1946 to 1955 at the Johns Hopkins University. He headed the Division of Climatic and Physiographic Research of the U.S. Soil Conservation Service from 1935 to 1942. From 1946 until his death, he was the director of the Laboratory of Climatology, at Seabrook, New Jersey, and professor of climatology at Drexel Institute of Technology, Philadelphia.

From 1941 to 1944, Thornthwaite was president of the section of METEOROLOGY of the American Geophysical Union. In 1951, he became president of the Commission on Climatology of the WORLD METEOROLOGICAL ORGANIZATION, a post he held until his death. He died from cancer on June 11, 1963.

Torricelli, Evangelista

(1608–1647)
Italian
Physicist and mathematician

The Italian physicist and mathematician who discovered the principle of the BAROMETER was born at Faenza, near Ravenna, on October 15, 1608. In 1627, he went to Rome to study science and mathematics at the Sapienza College. Having read some of the works of Galileo (1564–1642), he was inspired to write a treatise developing some of Galileo's ideas on mechanics.

Torricelli's teacher, a former student of Galileo, sent the treatise to Galileo, who was impressed. Galileo invited Torricelli to Florence, and in 1641 the two met. Galileo was then old and blind. Torricelli became his assistant, but Galileo died three months later. It was Galileo who suggested the problem that Torricelli solved.

The question was: Why does water rise up a cylinder when a piston in the cylinder is raised, but only so far? The conventional explanation for water rising in this way at all, which Galileo supported, was that raising the piston produces a vacuum in the cylinder and that nature abhors a vacuum, so the water is compelled to rise. It can be made to rise only about 33 feet (10 m) above its ordinary level, however, and that was the puzzle. Galileo suspected that nature's abhorrence of a vacuum was limited, so vacuums can be tolerated under certain conditions. He asked Torricelli to investigate.

Torricelli rejected the idea of "vacuum abhorrence." He considered what might happen if the air possessed weight. In his day most scientists believed air had a property of "levity," making it tend to rise, so Torricelli's idea was fairly radical. If air possessed weight, however, then the weight of air would press down on the surface of the water outside the cylinder. As the piston was raised, there would be a space containing no air between the bottom of the piston and the surface of the water. The air would not press down inside the cylinder below the piston, but it would still do so outside. Consequently, the pressure outside the cylinder would cause water to rise inside the cylinder as the piston was raised.

Suppose, though, that the pressure due to the weight of air was sufficient only to raise the water by 33 feet? In that case, 33 feet would be as far as the water could be made to rise, and withdrawing the piston further would have no effect.

In 1643, Torricelli tested this idea, choosing to use mercury, which is 13.6 times denser than water. He partly filled a dish with mercury and completely filled a glass tube 4 feet (1.2 m) long and open at one end. Placing his thumb over the open end, he inverted the tube of mercury and placed the open end below the surface of the mercury in the dish, holding the tube absolutely upright. When he removed his thumb, mercury flowed out of the tube and into the dish, but some mercury remained in the tube. The level of mercury in the tube was about 30 inches (760 mm) higher than the surface of the mercury in the dish.

Because the liquid had fallen from a full tube, rather than being drawn upward by the withdrawal of a piston, Torricelli had proved it was the pressure exerted by the weight of air on the mercury in the dish that supported the column of mercury in the tube. He had proved that air has weight, a finding with implications that were explored by Blaise Pascal (1623–62).

Above the mercury, the tube was empty except for a small amount of mercury vapor. Torricelli was the first person to make a vacuum, and a vacuum produced in this way is still known as a Torricellian vacuum.

Then Torricelli noticed that the height of the column of mercury varied slightly from day to day. He attributed this, correctly, to variations in the weight of the air. He had invented a device for measuring these small changes—the first barometer.

After Galileo's death, Torricelli was appointed mathematician to the grand duke as well as professor of mathematics in the Florentine Academy. He died in Florence on October 25, 1647.

Travers, Morris William

(1872–1961)
English
Chemist

Morris Travers collaborated with William Ramsay (1852–1916) in the work that led to the discovery of rare gases.

Travers was born in Kensington, London, on January 24, 1872, the second of four sons of a London physician. He was educated at schools in Ramsgate, Kent (1879–82) and Woking, Surrey (1882–85), before being sent to Blundell's School at Tiverton, Devon, chosen because it had a good chemistry laboratory. He enrolled at University College, London, in 1889, graduating in chemistry in 1893.

In 1894, he began to conduct research in organic chemistry at the University of Nancy, France, but after a few months he returned to University College and became a demonstrator, working under Ramsay. This was the start of the collaboration that led to their discoveries of ARGON, NEON, KRYPTON, and XENON. He received his D.Sc. in 1898 and was made an assistant professor. Travers became a full professor in 1903.

In 1906, Travers was appointed director of the Indian Institute of Scientists, in Bangalore, India. He returned to England at the outbreak of World War

I in 1914 to direct glass production at a factory in Walthamstow, London. He later became president of the Society of Glass Technology. He became interested in fuel technology, the gasification of coal, and in high-temperature furnaces. In 1927, he was appointed an honorary professor of chemistry at the University of Bristol. Travers retired in 1937.

During World War II, Travers was a consultant and adviser to the explosives section of the Ministry of Supply. He died at his home in Stroud, Gloucestershire, on August 25, 1961.

Tyndall, John

(1820–1893)
Irish
Physicist

John Tyndall was born at Leighlin Bridge, County Carlow, in southwestern Ireland, on August 2, 1820, the son of a police officer. He was educated at the school in the nearby town of Carlow, where he acquired a sound background in mathematics and English. He left school at 17, and two years later, in 1839, he joined the Ordnance Survey to train as a surveyor.

The Ordnance Survey is the British government agency responsible for mapping the country. In the 19th century, it was part of the military establishment. Tyndall worked on the survey of Ireland (which was then part of Britain), and when that task was completed, in 1842, he transferred to the English survey. He was dismissed in 1843, however, because he had complained about the efficiency of the Ordnance Survey and about its treatment of Irish people. He returned to Ireland, but then obtained a position with a firm of surveyors in England, so he returned and conducted surveys for the companies that were rapidly expanding the railroad network.

The railroad boom ended in 1847, and Tyndall found a post as a mathematics teacher at Queenwood College, Hampshire. There he became friendly with the science teacher, the chemist Edward Frankland (1825–99) and, through Frankland's influence, he developed an interest in science. The two men decided to further their education, and in October 1848 they enrolled together at the University of Marburg, Germany. Tyndall was then 28 years old.

Tyndall studied physics, calculus, and chemistry at Marburg. His chemistry teacher was Robert Bunsen (1811–99), after whom the laboratory Bunsen burner is named. Bunsen helped and encouraged Tyndall, who began the course with only a limited knowledge of German. Despite this, he qualified for a doctorate in 1850. He specialized in the study of magnetism and optics and continued his research for an additional year in Germany. Short of funds, in 1851 Tyndall returned to his post at Queenwood College, where he spent the next two years, supplementing his salary by translating and reviewing scientific articles from foreign journals.

By this time, Tyndall was beginning to earn the respect of other scientists. He was elected a fellow of the Royal Society in 1852, and in 1853 it was arranged that he should give a lecture at the Royal Institution in London. This was so successful that he was invited to give a second lecture, and then a whole course of lectures. A few months later, he was appointed professor of natural philosophy at the Royal Institution. Michael Faraday (1791–1867) was the superintendent of the Royal Institution. The two men were close friends, and when Faraday died Tyndall succeeded him as superintendent.

John Tyndall acquired a reputation as a brilliant and entertaining lecturer. In 1872 and 1873, he made a lecture tour of the United States. Tyndall paid the proceeds from those lectures into a trust for the advancement of American science. He was also a talented writer and journalist and did much to popularize science in Britain and the United States. From 1859 to 1868, Tyndall was also professor of physics at the Royal School of Mines, where he gave a series of popular lectures on science, working in collaboration with another close friend, Thomas Henry Huxley (1825–95). The success of those lectures prompted the British Association for the Advancement of Science to hold similar lectures at its annual meetings.

In addition to lecturing, teaching, and writing, Tyndall was also conducting his own research in the laboratories in the basement of the Royal Institution. At first these were on diamagnetism. Then, starting in January 1859, he studied radiant heat. He found that although OXYGEN, NITROGEN, and HYDROGEN are completely transparent to radiant heat (infrared radiation, *see* SOLAR SPECTRUM), other gases, especially WATER VAPOR, CARBON DIOXIDE, and OZONE, are relatively opaque. Tyndall said that without water vapor the surface of the Earth would be permanently frozen. Later, he speculated about the way changing the concentrations of these gases might affect the climate. This was the first suggestion of what is now known as the GREENHOUSE EFFECT.

In 1869, Tyndall discovered what is now called the Tyndall effect. He was investigating the way light passes through liquids and found that light passes unimpeded through a solution or pure solvent, but that the light beam becomes visible in a colloidal solution (*see* COLLOID). This suggested that although the colloidal particles cannot be seen, they are big enough to scatter light. From this he reasoned that particles in the atmosphere should also scatter light, and that air molecules should scatter blue light more than red light, causing the blue color of the sky. Lord Rayleigh (1842–1919) confirmed this in 1871. Tyndall used the effect to measure the pollution of London air. It also led him to suspect that the air may contain microscopic living organisms, and he was able to show in 1881 that bacterial spores are present in even the most carefully filtered air. This confirmed the rejection by Louis Pasteur (1822–95) of the idea that life is generated spontaneously from nonliving matter, and it provided added support to the germ theory of disease.

Tyndall had many interests. He was a keen mountaineer. He climbed Mont Blanc (15,781 feet, 4,813 m) several times and was the first person to climb the Weisshorn (14,804 feet, 4,515 m). In 1849, he and Huxley began to take annual vacations in the Alps. This led them to publish a treatise, *On the Motion and Structure of Glaciers,* about glacial movement. He also invented many scientific instruments. He led an active civic life, acting as a government adviser and helping to investigate the causes of mining and other industrial accidents. He was especially concerned about safety at sea.

Tyndall also devoted considerable energy to championing the cause of those he believed had been badly treated. In the 1860s, for example, he lectured widely on the work of the German physicist Julius Robert Mayer (1814–78). Mayer was years ahead of all his contemporaries in calculating the mechanical equivalent of heat. He proposed the conservation of energy (*see* THERMODYNAMICS, LAWS OF), and he suggested that solar energy is the ultimate source of all the energy on Earth and that solar energy is produced by the conversion of KINETIC ENERGY into radiant energy. Yet Mayer's work aroused little interest, and more famous scientists, including James Prescott Joule (1818–89), Hermann Ludwig Ferdinand von Helmholtz (1821–94), and Lord Kelvin (1824–1907) were given the credit for discoveries Mayer had made first. Mayer became so depressed at the lack of recognition and his complete failure to claim priority for his discoveries that in 1849 he attempted suicide, and in 1851 he was admitted to a mental institution that would be judged harsh and cruel by modern standards. Tyndall worked tirelessly to put right the wrongs Mayer had suffered, and he finally succeeded in having Mayer's achievements recognized.

In 1876, when he was 56, Tyndall married Louisa Hamilton. They had no children, but lived together devotedly until Tyndall's death.

Despite his energy, throughout his adult life Tyndall slept badly and was often unwell. By the 1880s, his health was deteriorating. He retired from the Royal Institution in 1887 and went to live at Hindhead, Surrey. He gave up most of his scientific work, but took an active part in political campaigns, including the campaign against the Home Rule Bill, which would have made Ireland independent of Britain. In 1891, for the first time in 30 years, he was too ill for his annual climbing vacation in the Alps. His insomnia became steadily worse, and he experimented with a variety of drugs to treat it. He died on December 4, 1893, after his wife had accidentally given him an overdose of the sedative chloral hydrate.

Further Reading

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Von Guericke, Otto

(1602–1686)
German
Physicist

Otto von Guericke carried out one of the most famous of all experiments, demonstrating beyond doubt that the atmosphere exerts pressure. He also demonstrated that Aristotle's assertion that a vacuum is impossible, summed up by medieval scholars in the saying "nature abhors a vacuum," was false. Vacuums can and do exist.

Von Guericke was born at Magdeburg on November 20, 1602. His family was wealthy, and Otto was able to study law, science, and engineering at the Universities of Leipzig (1617–20), Helmstedt (1620), Jena (1621–22), and Leiden (1622–25). He traveled in France and England. A Protestant city, Magdeburg suffered severe damage during the Thirty Years' War and most of its 40,000 population were killed. Guericke and his family fled to Brunswick and the city of Erfurt, where he worked as an engineer for the Swedish and later Saxon governments. On his return to Magdeburg in 1627, Guericke was made an alderman. As the war continued to rage, he represented Magdeburg in negotiations with various occupying powers. He was mayor of Magdeburg from 1646 until 1676, and in 1646 he was ennobled, becoming von Guericke.

Aristotle had proposed that a moving body will accelerate if the medium through which it travels becomes less dense, because it will encounter less resistance. This being so, a moving body entering a vacuum will accelerate to infinite speed. Aristotle did not believe infinite speed was possible, so he concluded that a vacuum cannot exist. In 1643, Evangelista Torricelli made his device to demonstrate that air has weight—the first BAROMETER—using a tube filled with mercury. When the level of the mercury in the tube fell, the empty space above the mercury contained nothing (apart from a small amount of mercury vapor). It was a vacuum.

Von Guericke determined to conduct a more convincing demonstration. In 1647, he built an air pump worked by human muscle and attached it to a copper vessel. Once the seals were airtight, he pumped air out of the vessel until it imploded. He followed this demonstration by others showing that after the air has been removed from a vessel a bell ringing inside the vessel cannot be heard clearly, that candles will not burn in the vessel, and that animals cannot survive in it.

In 1654, he constructed a cylinder and piston. He had 50 strong men pull on a rope attached to the piston. For all their strength they could pull it no more than halfway up the cylinder, and as von Guericke's pump removed the air, the men were unable to prevent the piston from moving back into the cylinder.

Von Guericke performed his most famous and most dramatic demonstration in 1657. This time he used two metal hemispheres that fitted together snugly along a greased flange. These came to be called the Magdeburg hemispheres. A team of horses was attached by ropes to each hemisphere, and von Guericke evacuated the air from inside. Try as they might, the two teams of horses could not pull the hemispheres apart. When von Guericke allowed air to enter the hemispheres, they immediately fell apart of their own accord.

Von Guericke had shown not simply that the atmosphere exerts pressure, but that it exerts very great pressure. He also experimented with the elasticity of air. Blaise Pascal had shown in 1648 that AIR PRESSURE decreases with height. Von Guericke explored the link between air pressure and weather conditions. Using a water barometer to monitor changes in air pressure, von Guericke began issuing weather forecasts, and in 1660 he proposed the establishment of a string of weather stations that would contribute data to a WEATHER FORECASTING system.

This remarkable man also demonstrated the magnetization of iron by hammering it in a north–south direction, and he devised a machine for producing static electricity by friction. He was interested in astronomy and suggested that comets return at regular intervals.

Von Guericke retired in 1681 and went to live with his son in Hamburg. He remained there for the rest of his life and died at Hamburg on May 11, 1686.

von Kármán, Theodore

(1881–1963)
Hungarian
Aerodynamicist

Theodore von Kármán studied the flow of fluids around cylinders, discovering that the wake separates into two rows of vortices, known as von Kármán vortex streets (*see* VORTEX). These vortices can cause vibrations that are serious enough to damage structures. The spiral fluting around many factory chimneys are designed to prevent vortex streets forming.

Von Kármán was born in Budapest on May 11, 1881. His father, Mór, was a professor at the University of Budapest. Theodore studied engineering at the Budapest Royal Polytechnic University, graduating in 1902. In 1903, he was appointed an assistant professor there. He studied for his doctorate at the University of Göttingen, Germany, where he helped design a wind tunnel for airship research. He obtained his doctorate in 1909.

During World War I, von Kármán served in the Austro-Hungarian army, but apart from that interlude he spent the years between 1913 and 1930 directing aeronautical research at the Aachen Institute, Germany. He visited the United States in 1926, and in 1928 he began to divide his time between Aachen and the Guggenheim Aeronautical Laboratory at the California Institute of Technology. He became director of the Guggenheim Laboratory and concentrated his research on aerodynamics.

Theodore von Kármán died at Aachen, while on vacation visiting a friend, on May 7, 1963.

Vonnegut, Bernard

(1914–1997)
American
Physicist

Bernard Vonnegut was born at Indianapolis, Indiana, on August 29, 1914. He was educated at the Massachusetts Institute of Technology (M.I.T.), graduating in 1936. He obtained his Ph.D. from M.I.T. in 1939 for research into the conditions that produce icing on aircraft (*see* FLYING CONDITIONS). From 1939 until 1941, he worked for the Hartford Empire Company, and from 1941 until 1945 Vonnegut was a research associate at M.I.T.

In 1945, Bernard Vonnegut moved to the laboratories of the General Electric Corporation in Schenectady, New York, where he continued his research into icing in collaboration with Vincent Schaefer (1906–93). Following the discovery that dry ice (solid CARBON DIOXIDE) was effective at CLOUD SEEDING, Vonnegut turned his attention to the search for other materials that might perform the same task. Deciding that crystals of silver iodide were the right size and shape to act as FREEZING NUCLEI, he experimented with them and was proved correct. Silver iodide largely replaced dry ice as a seeding medium. Unlike dry ice, it can be stored indefinitely at room temperature and it does not have to be released from an airplane flying above the target cloud. Silver iodide can be released at ground level and will be carried into the cloud by vertical air currents. If dry ice were released in this way, it would vaporize before it could cause ice DEPOSITION.

Vonnegut moved to the Arthur D. Little Corporation in 1952, and in 1967 he was appointed Distinguished Research Professor of the State University of New York, a position he held until his death at Albany, New York, on April 25, 1997.

Wegener, Alfred Lothar

(1880–1930)
German
Meteorologist and geologist

Alfred Wegener is best known for having formulated the theory of CONTINENTAL DRIFT that developed later into the theory of PLATE TECTONICS. He was primarily a meteorologist, however, and studied the formation of RAINDROPS and the circulation of air over polar regions.

Alfred Wegener was born in Berlin on November 1, 1880. His father was a minister and director of an orphanage. Alfred was educated at the Universities of Heidelberg, Innsbruck, and Berlin. In 1905, he received a Ph.D. in planetary astronomy from the University of Berlin, but immediately switched to METEOROLOGY, taking a job at the Royal Prussian Aeronautical Observatory, near Berlin. He used kites and balloons to study the upper atmosphere and also flew hot air balloons. In 1906, Alfred and his brother Kurt remained airborne for more than 52 hours, breaking the world endurance record.

In 1906, he joined a Danish two-year expedition to Greenland as the official meteorologist. Wegener studied the polar air, using kites and tethered balloons, and on his return to Germany in 1909 he became a lecturer in meteorology and astronomy at the University of Marburg. He collected his lectures into a book published in 1911, *Thermodynamik der Atmosphäre* (Thermodynamics of the atmosphere). This became a standard textbook throughout Germany. In it, Wegener pointed out that where ICE CRYSTALS and supercooled droplets (*see* SUPERCOOLING) are present together, the crystals will grow at the expense of the droplets, because the equilibrium vapor pressure (*see* WATER VAPOR) is lower over the crystals. He suggested that this might lead to the formation of crystals that were large enough to sink through the cloud and melt at lower levels to become raindrops. Wegener never had an opportunity to test this idea in real clouds. Tor Bergeron and Walter Findeisen finally tested it in the 1930s. Bergeron acknowledged his debt to Wegener, and although this type of raindrop formation is usually known as the Bergeron-Findeisen mechanism, it is sometimes called the Wegener-Bergeron-Findeisen mechanism.

Wegener was also the first person to explain two kinds of arc that are occasionally seen in the Arctic opposite the Sun. The arcs are caused by ice crystals that form in the very cold air. They are now called Wegener arcs.

Since 1910, Wegener had been intrigued by the apparent fit of the continental coastlines on either side of the Atlantic Ocean. In 1912, he published a short book, *Die Entstehung der Kontinente und Ozeane* (*The Origin of the Continents and Oceans*), drawing together various strands of evidence to support the idea that he called "continental displacement." This proposed that the continents had once been joined and that they have moved slowly to their present positions.

It was also in 1912 that Wegener married Else Köppen, the daughter of Wladimir Köppen (1846–1940), the most eminent climatologist in Germany. Wegener and Köppen collaborated in a book about the history of climate, *The Climates of the Geological Past*. Wegener then returned to Greenland to take part in the four-man 1912–13 expedition. The team crossed the ice cap and was the first to spend the winter on the ice.

On the outbreak of war in 1914, Wegener was drafted into the German army, but was wounded almost at once. He spent a long time recuperating, during which he elaborated on his theory of continental drift, publishing an expanded version of *The Origin of the Continents and Oceans* in 1915 (it was not translated into English until 1924). The book received a hostile reception from German scientists, and Wladimir Köppen strongly disapproved of his son-in-law's digression from meteorology into geophysics. Wegener spent the remainder of the war employed in the military meteorological service.

After the war, Wegener returned to Marburg. In 1924, he accepted a post created especially for him and became the professor of meteorology and geophysics at the University of Graz, in Austria.

In 1930, he returned to Greenland once more, this time as the leader of a team of 21 scientists and technicians planning to study the climate over the ice cap. They intended to establish three bases, all at 71°N, one on each coast and one in the center, but they were delayed by bad weather. On July 15, a party left to establish the central base, called Eismitte, 250 miles (402 km) inland. The weather then prevented necessary supplies from reaching them, including the radio transmitter and hut in which they were to live. On September 21, Wegener, accompanied by 14 others, set off with 15 sleds to carry supplies to Eismitte. The appalling conditions forced all but Wegener, Fritz Lowe, and Rasmus Villumsen to give up and return. These three finally reached Eismitte on October 30. Lowe was exhausted and badly frostbitten. They stayed long enough to celebrate Wegener's 50th birthday on November 1, then Wegener and Villumsen began their return, leaving Lowe to recover. They never reached the base camp. At first it was assumed they had decided to overwinter at Eismitte, but when they had still not appeared in April a party went in search of them. They found Wegener's body on May 12, 1931. He appeared to have suffered a heart attack. Villumsen had carefully buried the body. They marked the site with a mausoleum made from ice blocks, later adding a large iron cross. Despite a long search, Villumsen was never found.

There is now an Alfred Wegener Institute for Polar and Marine Research at Bremerhaven, Germany.

Further Reading

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Wien, Wilhelm

(1864–1928)
German
Physicist

WIEN'S LAW describes the relationship between the TEMPERATURE of a BLACKBODY and the wavelength (*see* WAVE CHARACTERISTICS) of its maximum emission of radiation. Its author, Wilhelm Wien, received the 1911 Nobel Prize in physics for his work on blackbody radiation.

Wilhelm Wien was born at Fischhausen, in East Prussia (now in Poland), on January 13, 1864. His father, Carl Wien, was a landowner. Wilhelm might have become a gentleman farmer, but he was determined to obtain a good education. In 1866, the family moved to Rastenburg, East Prussia, and in 1879 Wilhelm enrolled at a school in that town. From 1880 until 1882, he studied at the City School in Heidelberg, and in 1882 he entered the University of Göttingen to study mathematics and natural sciences. Later in the same year, he moved to the University of Berlin. While still a student, from 1883 until 1885, he worked as an assistant to Hermann von Helmholtz (1821–94). He obtained his doctorate in 1886, with a thesis on the diffraction of light on sections of metals and the influence of different materials on the color of refracted light.

Carl Wien then fell ill, and between 1886 and 1890 Wilhelm had to spend most of his time helping to manage the family estate, although he did manage to spend one semester working with Helmholtz. Wien returned to Helmholtz's laboratory when the estate was sold, remaining there until 1896, when he was appointed professor of physics at the University of Aix-la-Chapelle (also called Aachen). In 1899, he became professor of physics at the University of Giessen, and in 1900 professor of physics at Würzburg. In 1902, he succeeded Ludwig Boltzmann (1844–1906) as professor of physics at the University of Leipzig, and in 1906 he became professor of physics at the University of Berlin.

It was in 1893 that Wien published the law relating radiation emission to temperature, known as the law of displacement. The following year he defined an ideal body that absorbs all the radiation falling upon it. He called such a body a blackbody. He published Wien's law in 1896. It was shown later that Wien's law applies only to short-wave radiation. Lord Rayleigh (1842–1919) had published an equation that applied to long-wave radiation, and the attempt to devise an equation that was valid at all wavelengths drew the German physicist Max Planck (1858–1947) to develop quantum theory.

In later years, Wien turned his attention to X-rays and cathode rays, confirming that cathode rays are streams of electrons.

Wilhelm Wien died at Munich, Bavaria, on August 31, 1928.

APPENDIX II
TROPICAL CYCLONES AND TROPICAL STORMS

Abby A typhoon that struck Taiwan on September 19, 1986; it killed 13 people and caused damage estimated at $80 million.

Abe A typhoon that struck Zhejiang Province, China, on August 31, 1990; it killed 48 people.

Aere A typhoon that struck northern Taiwan on August 24, 2004, killing at least 24 people. Aere then moved on to the Philippines, where five persons lost their lives.

Agnes A hurricane, rated category 1 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Florida and New England in 1972; it caused $2.1 billion of damage.

Agnes is also the name of two typhoons. The first struck South Korea on September 1, 1981; it delivered 28 inches (711 mm) of rain in two days and left 120 people either dead or missing.

The second Typhoon Agnes, rated category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, struck the central Philippines in November 1984; it generated winds of 185 MPH (297 km/h). At least 300 people were killed and 100,000 rendered homeless. The damage was estimated at $40 million.

Alex A typhoon that struck Zhejiang Province, China, on July 28, 1987. It triggered a huge landslide. There was widespread damage, and at least 38 people were killed.

Alicia A hurricane, rated category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck southern Texas on August 18, 1983. It generated winds of 115 MPH (185 km/h) and caused extensive damage in Galveston and Houston. At least 17 people were killed, and the damage was estimated at $1.6 billion.

Allen A hurricane, rated category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck islands in the Caribbean and the southeastern United States in August 1980. It brought winds of 175 MPH (280 km/h) gusting to 195 MPH (314 km/h). Barbados, St. Lucia, Haiti, the Dominican Republic, Jamaica, and Cuba were affected. More than 270 people died, most of them in Haiti.

Allison A tropical storm that moved across the southeastern United States from June 6 to 17, 2001. At least 20 people lost their lives in Texas, two in Louisiana, nine in Florida, nine in North Carolina, six in Pennsylvania, and one in Virginia. The damage was estimated to cost $5 billion.

Alpha A tropical storm that formed over the Caribbean on October 22, 2005. On October 23, it reached Haiti and the Dominican Republic, bringing heavy rain and killing at least 26 people. Alpha was the 22nd named storm of the 2005 season, breaking a record set in 1933 and making 2005 the most active hurricane season ever recorded.

Ami A category 3 cyclone that struck Fiji in January 2003 with winds of up to 125 MPH (200 km/h) and waves up to 98 feet (30 m) high. It killed 11 people.

Amy A typhoon that struck southern China on July 20 and 21, 1991. It killed at least 35 people and injured 1,360.

Andrew A hurricane, rated as category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck the Bahamas, Florida, and Louisiana from August 23 to 26, 1992. It generated winds of up to 164 MPH (264 km/h). It was the costliest hurricane in United States history up to that time. In Florida, Homestead and Florida City were almost destroyed, 38 people were killed, 63,000 homes were destroyed, and damage was estimated at $20 billion. In Louisiana, 44,000 people were rendered homeless and damage was estimated at $300 million.

Angela Two typhoons, the first of which struck the Philippines in October 1989. It killed at least 50 people.

The second Typhoon Angela, rated at category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, struck the eastern Philippines on November 3, 1995, generating winds of 140 MPH (225 km/h). It killed more than 700 people, rendered more than 200,000 homeless, and destroyed 15,000 homes. The cost of damage to crops, roads, and bridges was estimated at $77 million.

Audrey A hurricane, rated category 3 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck the U.S. Gulf Coast near the border between Louisiana and Texas on June 17, 1956. It killed nearly 400 people and generated winds of 100 MPH (160 km/h) and a STORM SURGE of 12 feet (3.6 m).

Babs A typhoon that struck the Philippines in late October 1998. It caused floods and landslides in which at least 132 people died and about 320,000 people were rendered homeless.

Bebinca A typhoon that struck the Philippines in November 2000. It left 43 people dead and forced more than 630,000 people to leave their homes in metropolitan Manila and in 14 northern provinces.

Benedict One of five cyclones that struck Madagascar between January and March 1982. The others were called Frida, Electra, Gabriel, and Justine. Together they killed more than 100 people and rendered 117,000 homeless.

Bertha A hurricane that struck the U.S. Virgin Islands on July 8, 1996, bringing torrential rain and winds of up to 103 MPH (166 km/h) and triggering FLASH FLOODS and mudslides. It then moved to the British Virgin Islands, St. Kitts and Nevis, and Anguilla. It reached the Bahamas on July 10, where it caused waves 20 feet (6 m) high and winds of 100 MPH (160 km/h). On July 12, it crossed the Carolina coast then traveled north, eventually reaching Delaware and New Jersey. Bertha was initially rated as category 1 on the SAFFIR/SIMPSON HURRICANE SCALE, but was then upgraded to 2 and on July 9 it reached category 3. It was a large hurricane, with a diameter of 460 miles (740 km), and produced hurricane-force winds (*see* BEAUFORT WIND SCALE) 115 miles (185 km) from the eye. It killed seven people.

Bilis A typhoon that struck Taiwan and the coast of mainland China in August 2000. It killed 11 people in Taiwan, including seven farmers and a six-year-old girl who were buried in a mudslide and a woman who was killed by a falling power line. The typhoon had weakened by the time it reached the mainland province of Fujian, but it destroyed more than 1,000 homes.

Bob A hurricane that struck the eastern coast of the United States from August 18 to 20, 1991. It killed at least 20 people.

Brenda A typhoon that struck southern China in May 1989, killing 26 people.

Bret A tropical storm that struck Venezuela on August 8, 1993, causing floods and mudslides in which at least 100 people died.

Bret is also the name of a hurricane that struck the coast of Texas in 1999. With winds of 125 MPH (201 km/h), it struck Kenedy County at about 6 P.M. on August 22, traveling westwards at about 7 MPH (11.25 km/h). Its winds later weakened to 105 MPH (169 km/h). The following day it was downgraded to a tropical storm and its winds abated. The area affected was sparsely populated, but four people lost their lives in floods caused by the hurricane.

Calvin A hurricane that struck Mexico on July 6 and 7, 1993. It killed 28 people.

Camille A hurricane, rated category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Mississippi and

Louisiana on August 17 and 18, 1969, killing about 250 people along the coast and causing $1.42 billion of damage. Camille then weakened and headed south and then east, over the Blue Ridge Mountains, Virginia, and was funneled through the narrow valleys of the Rockfish and Tye Rivers, where it encountered an advancing cold FRONT with associated THUNDERSTORMS. This resulted in 18 inches (457 mm) of rain that flooded 471 square miles (1,220 km^2). FLASH FLOODS damaged or destroyed 185 miles (298 km) of road, and 125 people died, either drowned or crushed by boulders. After 80 days the floods subsided.

Carlotta A hurricane that formed off the Mexican coast on June 19, 2000. It headed out to sea, but generated heavy rain that caused mudslides, killing at least six people and causing more than 1,000 people to leave their homes.

Catarina A hurricane that developed in the South Atlantic Ocean during the week of March 22–28, 2005, and made landfall on the coast of the Brazilian state of Santa Catarina on March 28, with winds estimated at nearly 90 MPH (145 km/h). Catarina caused extensive damage, and some lives were lost. Catarina is believed to be the first tropical cyclone ever recorded in the South Atlantic.

Cecil Two typhoons, the first of which struck South Korea in August 1982. It killed at least 35 people and caused damage estimated at more than $30 million.

The second Typhoon Cecil struck Vietnam on May 25 and 26, 1989. It destroyed 36,000 homes and killed at least 140 people.

Charley A hurricane that reached the British Isles, where it arrived on August 25, 1986. It caused at least 11 deaths.

A second hurricane Charley struck southwestern Florida on August 13, 2004, devastating Punta Gorda and Port Charlotte, and killing 27 people.

Chata'an A typhoon that struck Japan in July, 2002, killing five people and causing widespread flooding.

Chebi A typhoon that struck Taiwan and Fujian Province, China, on June 23–24, 2001. It killed at least 73 in Fujian and nine in Taiwan.

Clara A typhoon that struck Fujian Province, China, on September 21, 1981. It destroyed 130 square miles (337 km^2) of rice crops.

Clare A category 2 cyclone that struck Western Australia at about midnight on January 9, 2006. The storm made landfall near Dampier, with winds of up to 87 MPH (140 km/h), causing minor damage and no injuries.

Cobra A typhoon, generating winds up to 130 MPH (208 km/h) and waves up to 70 feet (21 m) high, that occurred in the Philippine Sea in December 1944. It struck a U.S. naval fleet, causing three destroyers to sink and destroying 150 carrier-borne aircraft. It caused the deaths of 790 sailors.

Connie A hurricane that struck the United States in August, 1957, producing rain that saturated the ground, shortly before the arrival of Hurricane Diane.

Damrey A typhoon that crossed East Asia for a week in September 2005. It killed 36 people in Vietnam, 16 in the Philippines, 16 in southern China, and at least three in Thailand. On September 28, Damrey was downgraded to a tropical depression.

Dan A typhoon that struck the Philippines on October 10, 1989. It killed 43 people and rendered 80,000 homeless.

Dan was also the name of a typhoon that struck the Philippines in October 1999 and then weakened to a tropical storm as it approached the outlying Taiwanese islands of Penghu and Kinmen. In the Philippines at least eight people were killed, thousands of homes were flooded, and the cost of damage to crops was estimated as $2 million.

David A hurricane, rated category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck islands in the Caribbean and the eastern coast of the United States in late August and early September 1979. It brought winds of up to 150 MPH (240 km/h), killed more than 1,000 people, and caused damage estimated at billions of dollars. The hurricane affected the Dominican Republic, Dominica, Puerto Rico, Haiti, Cuba, the Bahamas, Florida, Georgia, and New York State.

Dawn A typhoon that struck central Vietnam on November 19 to 23, 1998. It was the worst storm to affect the country in 30 years. More than 100 people were killed, and about 200,000 were forced to leave their homes.

Dennis A hurricane that struck Haiti on July 7, 2005, killing at least 60 people. On July 8, Dennis reached Cuba, where 16 people lost their lives.

Diane A hurricane that struck the United States in August 1957. It killed more than 190 people and caused $1.6 billion of damage.

Dolly A tropical storm that struck islands in the Caribbean on August 20, 1996, strengthening to hurricane force as it reached Punta Herrero, Mexico. It then weakened but strengthened to hurricane force again as it moved across the sea toward northeastern Mexico and Texas.

Dolores A hurricane, with extremely heavy rain, that struck an area housing poor people on the outskirts of Acapulco, Mexico, on June 17, 1974. At least 13 people died, and 35 were injured.

Domoina A cyclone that struck Mozambique, South Africa, and Swaziland from January 31 to February 2, 1984. It caused severe flooding in which at least 124 people died and thousands were rendered homeless.

Dot A typhoon that struck Luzon, Philippines, on October 19, 1985. It destroyed 90 percent of the buildings in the city of Cabanatuan, killed at least 63 people, and caused damage estimated at $1 billion.

Eline A cyclone that struck Mozambique on February 22, 2000. It produced winds of up to 160 MPH (257 km/h) and torrential rain. There were reports of coastal villages being swept away by the STORM SURGE.

Eloise A hurricane, rated category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck several Caribbean islands and the eastern United States in September 1975. It reached Puerto Rico on September 16, bringing winds of up to 140 MPH (225 km/h) and heavy rain, and killing 34 people. It then moved to Hispaniola, where 25 people died. It crossed Haiti and the Dominican Republic and from there reached Florida, where 12 people were killed. Eloise then moved northward along the coast as far as the northeastern United States, where a state of emergency was declared.

Elsie A typhoon that struck the Philippines on October 19, 1989; it killed 30 people and left 332,000 homeless.

Eric One of two cyclones that struck Viti Levu, Fiji, on January 22, 1985. The other was Nigel. Between them they caused the deaths of 23 people. It is most unusual for two cyclones to occur so close together.

Eve A typhoon that struck the southern tip of Kyushu, Japan, on July 18, 1996, bringing winds of 199 MPH (191 km/h).

Faith One of two tropical storms that struck central Vietnam in December 1998. Between them, Faith and Gil brought rain that caused floods in which at least 22 people died and thousands had to leave their homes.

Faye A typhoon that struck South Korea in July 1995; it killed at least 16 people.

Fifi A hurricane, rated category 3 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Honduras on September 20, 1974. It generated winds of 130 MPH (209 km/h) and heavy rain. An estimated 5,000 people were killed, and tens of thousands were rendered homeless.

Firinga A cyclone, rated category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck the island of Réunion, in the Indian Ocean, on January 28 and 29, 1989. It generated wind speeds of more than 125 MPH (200 km/h). At least 10 people died and 6,000 were rendered homeless.

Flo A typhoon that struck Honshu, Japan, on September 16 and 17, 1990; it killed 32 people.

Floyd A hurricane that formed in September 1999 and at its peak generated winds of 155 MPH (249 km/h), making it category 4 bordering category 5 on the SAFFIR/SIMPSON HURRICANE SCALE. It was also unusually large, with a diameter of about 600 miles (965 km).

Floyd struck the Bahamas on September 14 and then moved northward along the eastern coast of the

United States, reaching New York and New Jersey on September 16, by which time it had been downgraded to a tropical storm, with winds of 65 MPH (105 km/h). It brought heavy rain, causing flooding, and STORM SURGES of up to 7 feet (2.1 m). More than 2.3 million people were evacuated from their homes in Florida, Georgia, and the Carolinas. Crop damage in North Carolina was estimated to cost more than $1 billion. A total of 49 people lost their lives, one of them in the Bahamas and the remainder in the United States, 23 of them in North Carolina.

Forest A typhoon that struck the Japanese islands of Honshu, Kyushu, and Shikoku on September 19, 1983. It delivered up to 19 inches (483 mm) of rain, causing flooding that inundated 30,000 homes and resulted in the deaths of 16 people.

Fran A typhoon, rated category 3 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck southern Japan from September 8 to 13, 1976. It generated winds of 100 MPH (160 km/h) and brought 60 inches (1,524 mm) of rain. It caused the deaths of 104 people and made an estimated 325,000 homeless.

Hurricane Fran, rated as category 3, struck the eastern United States in September 1996. It triggered TORNADOES and produced a STORM SURGE with waves of up to 12 feet (3.6 m) and in some places 16 feet (4.8 m). It passed Cape Fear, North Carolina, on September 6 and the following day crossed North and South Carolina, Virginia, and West Virginia. More than 500,000 people were evacuated from the coastal areas of South Carolina, and areas of North Carolina were also evacuated. It killed 34 people.

Frankie A tropical storm that crossed from the Gulf of Tonkin to the Red River delta, Vietnam, on July 23, 1996. It killed 41 people.

Fred A typhoon that struck Zhejiang Province, China, on August 20 and 21, 1994. It killed about 1,000 people and caused damage estimated at more than $1.1 billion.

Frederic A hurricane that struck the eastern coast of Florida, Alabama, and Mississippi in September 1979. About eight people died, and 500,000 were evacuated.

Gafilo A cyclone that struck Madagascar on February 24, 2004, killing approximately 200 people and leaving thousands homeless.

Gavin A cyclone that struck Fiji in March 1997. It killed at least 26 people, 10 of whom died when a fishing trawler sank.

Gay A typhoon that struck Thailand on November 4 and 5, 1989. It killed 365 people and destroyed or damaged 30,000 homes.

Geralda A cyclone, rated as category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Madagascar from February 2 to 4, 1994. It generated winds of up to 220 MPH (354 km/h) and destroyed 95 percent of the buildings in the port of Toamasina. It killed 70 people and rendered 500,000 homeless.

Gert A hurricane that struck Bermuda in September 1999. At its peak it generated winds of 145 MPH (233 km/h) and was classed as category 4 on the SAFFIR/SIMPSON HURRICANE SCALE. By the time the edge of the hurricane reached Bermuda the wind speed had fallen to 110 MPH (177 km/h). Gert generated a STORM SURGE of 5 feet (1.5 m) and waves 10 feet (3 m) high, but caused no deaths or serious injuries.

Gilbert A hurricane, rated category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck islands in the Caribbean and the Gulf Coast in the United States from September 12 to 17, 1988. It caused widespread damage in Jamaica before moving toward the Yucatán Peninsula, Mexico. It killed about 200 people and caused an estimated $10 billion of damage in Monterrey, Mexico. In Texas, it killed at least 260 people and generated nearly 40 TORNADOES. The core pressure in Gilbert fell to 888 mb, making it the strongest hurricane recorded until that time. Its record was broken in 2005 by hurricane Wilma.

Gladys A typhoon that struck South Korea on August 23, 1991. It brought 16 inches (406 mm) of rain to Pusan and Ulsan, killing 72 people and rendering 2,000 homeless.

Glenda A category 4 cyclone that struck the northwestern coast of Australia on March 30, 2006, with winds of up to 155 MPH (250 km/h). The cyclone caused damage in the town of Onslow, but there were no reports of injuries. The cyclone was later downgraded to category 2.

Gloria A typhoon that struck the Philippines on July 25, 1996. It killed at least 30 people. It was then downgraded to a tropical storm. It reached Taiwan and the southeastern coast of China on July 26, where it killed three people.

Gordon A typhoon that struck Luzon, Philippines, on July 16, 1989. At least 200 people were killed.

Tropical Storm Gordon struck islands in the Caribbean, Florida, and South Carolina from November 13 to 19, 1994. It killed 537 people and caused damage estimated as at least $200 million.

Harvey A tropical storm, with 60-MPH (96-km/h) winds, that brought more than 10 inches (254 mm) of rain to southwestern Florida in September 1999.

Hazel A hurricane that struck islands in the Caribbean and the eastern United States in October 1954. It formed in the Lesser Antilles, then struck Haiti, South Carolina, North Carolina, Virginia, Maryland, Pennsylvania, New Jersey, and New York State, then continued into Canada. On October 18, the hurricane moved out into the Atlantic, eventually causing strong winds and heavy rain in Scandinavia. It killed an estimated 1,000 people in Haiti, 95 in the U.S., and 80 in Canada, and caused $250 million of damage in the United States and $100 million in Canada.

Herb A typhoon that struck Taiwan on July 31, 1996. It brought 44 inches (1,118 mm) of rain in 24 hours to Mount Ali, Taiwan, flooding thousands of homes. It killed at least 41 people. Herb then crossed the Taiwan Strait, reaching Pingtan, in Fujian Province, China, on August 1.

Higos A typhoon that struck Japan on October 2, 2002. It passed across Tokyo, then moved northward to Hokkaido. The storm caused at least four deaths and widespread flooding.

Honorinnia A cyclone that struck Madagascar on March 17, 1985. It destroyed 80 percent of the buildings in Toamasina and left 32 people dead and 20,000 homeless.

Hortense A tropical storm that struck Martinique on September 7, 1996 and then headed for the British Virgin Islands, Puerto Rico, and the Dominican Republic. By September 10, it had strengthened to a category 1 hurricane on the SAFFIR/SIMPSON HURRICANE SCALE. It then moved to the Bahamas and Turks and Caicos Islands. It killed 16 people in Puerto Rico and the Dominican Republic.

Hugo A hurricane, rated category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck islands in the Caribbean and the eastern coast of the United States from September 17 to 21, 1989, generating winds of up to 140 MPH (224 km/h). On September 11, Hugo reached Guadeloupe, where it killed 11 people. It reached Dominica in the Lesser Antilles (Leeward Islands) on September 17. Then it moved to St. Croix, St. John, St. Thomas, and the smaller islands of the U.S. Virgin Islands and Puerto Rico, arriving on September 19.

Hugo killed 10 people on Montserrat, six in the Virgin Islands, and 12 in Puerto Rico. Almost the entire population of Montserrat was made homeless, as well as 90 percent of the population of St. Croix and 80 percent of the people of Puerto Rico, and 99 percent of all homes were destroyed in Antigua.

Hugo then turned north and weakened to category 4. On September 21, it struck Charleston, South Carolina, where one person died when a house collapsed. At Folly Beach, South Carolina, 80 percent of the population was left homeless. The following day Hugo reached Charlotte, North Carolina, where one child was killed. It crossed the Blue Ridge Mountains the same day and in the afternoon moved across Virginia, where two people died and winds of 81 MPH (130 km/h) were recorded. There was a STORM SURGE at Awendaw, South Carolina, and the storm triggered several TORNADOES that caused damage on several islands and on the mainland in North Carolina. In all, the hurricane caused damage in the United States estimated at $10.5 billion.

Hyacinthe A cyclone that struck the island of Réunion, in the Indian Ocean, in January 1980. At least 20 people were killed.

Ike A typhoon that struck the Philippines on September 2 and 3, 1984. It killed more than 1,300 people and left 1.12 million homeless. It then struck the coast of Guangxi Zhuang, China, on September 6, where it caused widespread damage and killed 13 fishermen whose boats were lost at sea.

Imbudo A typhoon that struck Guangdong Province and the Guanxi region of China on July 26, 2003, killing at least 20 people.

Irene A hurricane that struck Caribbean islands and then moved to Florida and North Carolina in October 1999. It formed as a tropical storm over the northwestern Caribbean and reached hurricane force, category 1 on the SAFFIR/SIMPSON HURRICANE SCALE, as it approached Cuba. Irene reached Florida, moved from there to North Carolina, and then traveled out into the Atlantic. Although its winds were not strong, Irene brought very heavy rain and triggered several TORNADOES. Two people were killed in Cuba, five in Florida, and in North Carolina one person died in a traffic accident caused by the hurricane.

Iris A hurricane that struck southern Belize on October 8–9, 2001, destroying at least 3,000 houses, leaving 12,000 people homeless, and killing 22.

Irma Two typhoons, the first of which, rated category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, struck the Philippines on November 24, 1981. It generated winds of 140 MPH (225 km/h) and caused great destruction in the coastal towns of Garchitorena and Caramoan. More than 270 people were killed, and 250,000 were rendered homeless. The damage was estimated at $10 million.

The second Typhoon Irma struck Japan on July 1, 1985. It caused the deaths of 19 people and extensive damage in Numazu and Tokyo.

Irving A typhoon that struck Thanh Hoa Province, Vietnam, on July 24, 1989. At least 200 people were killed.

Isabel A hurricane that struck the United States on September 18, 2003. It caused serious damage, especially in North Carolina and Virginia, and approximately seven persons lost their lives in seven states.

Ismael A hurricane that struck Mexico on September 14, 1995. It killed at least 107 people in the northwestern states, many of them fishermen who were lost at sea.

Ivan A hurricane that crossed the Caribbean from September 7 to 17, 2004. It killed 39 people in Grenada and destroyed the island's crops, then killed 18 people in Jamaica. It strengthened before striking the Gulf Coast of the United States, where approximately 52 people lost their lives in several states.

Jeanne A tropical storm that struck the Gonaïve region of Haiti on September 18, 2004. The area had already been devastated by floods in May, and the flooding due to Jeanne killed more than 3,000 persons.

Joan A hurricane that struck the Caribbean coast of Central and South America from October 22 to 27, 1988. It caused severe damage and killed at least 111 people in Nicaragua, Costa Rica, Panama, Colombia, and Venezuela. It then weakened and was renamed Tropical Storm Miriam. Miriam struck El Salvador, where it rendered 3,000 people homeless.

Joe A typhoon that struck northern Vietnam on July 23, 1980. More than 130 people were killed and about 3 million were made homeless.

John A cyclone from the Indian Ocean that struck the sparsely populated northwestern coast of Australia on December 15, 1999. At its full strength it brought sustained winds of 130 MPH (209 km/h) and gusts of up to 185 MPH (298 km/h), making it the most powerful storm ever recorded in Australia up to that time. It crossed the coast near Whim Creek (estimated population 12), Western Australia, weakening as it did so, but still with sustained winds of 106 MPH (170 km/h). The cyclone brought STORM SURGES of up to 20 feet (6 m).

Jose A hurricane, rated category 2 on the SAFFIR/SIMPSON HURRICANE SCALE, with winds of 100 MPH (160 km/h), but later downgraded to a tropical storm with 65-MPH (105-km/h) winds, that struck Caribbean islands in October 1999. At its maximum extent its diameter was about 300 miles (480 km). It caused heavy rain, but no deaths and few serious injuries.

Judy Three typhoons, the first of which struck South Korea on August 25 and 26, 1979. It caused severe flooding in which 60 people died and 20,000 were rendered homeless.

The second Typhoon Judy, rated category 3 on the SAFFIR/SIMPSON HURRICANE SCALE, struck Japan on September 11 and 12, 1982. It killed 26 people and caused extensive damage.

The third Typhoon Judy struck South Korea in July 1989 and killed at least 17 people.

Kaemi A tropical storm that struck Vietnam on August 22, 2000. It killed 14 people.

Kai Tak A typhoon that struck the Philippines, Japan, and Taiwan in July 2000, with winds of 93 MPH (150 km/h) and heavy rain. Kai Tak arrived soon after typhoon Kirogi. Between them, the two typhoons killed 42 people in the Philippines, five in Japan, and one in Taiwan.

Kate A hurricane that struck Cuba and Florida from November 19 to 21, 1985. It killed at least 24 people.

Katrina The hurricane that brought the worst natural disaster to strike the United States for a century made landfall early on August 29, 2005, near Buras, Louisiana. By the time the hurricane dissipated two days later, Louisiana, Mississippi, and Alabama had suffered severe devastation. The storm had also caused damage in Florida, and its effects were felt in Texas, Arkansas, Georgia, and Tennessee. New Orleans was left flooded and largely abandoned, a ghost town. Biloxi, Mississippi, was almost totally demolished by the wind and 30-foot (9-m) STORM SURGE, and most of the buildings in nearby Gulfport were damaged and many destroyed. There was extensive flooding in Mobile, Alabama. The hurricane then headed northward. It was downgraded to a tropical storm, and it reached Clarksville, Tennessee, as a tropical depression. Its last known position was over southeastern Quebec and northern New Brunswick, Canada, where what remained of Katrina merged with an ordinary frontal weather system. By that time it brought nothing more serious than moderate rainfall.

New Orleans was battered by the winds, but suffered principally from the rain, which fell over the region draining into the Mississippi River and Lake Pontchartrain. Early on August 30, the pressure of water breached the levees protecting New Orleans in three places on the Lake Pontchartrain side of the city. Floodwater poured into New Orleans, rendering most of the city uninhabitable.

Katrina triggered TORNADOES in Pennsylvania, Virginia, Georgia, and Alabama. These caused several injuries, although no fatalities, but damage to poultry houses in Carroll County, Georgia, led to the death or liberation of 500,000 chickens.

The surface atmospheric pressure in the eye of the storm is the principal measurement used to evaluate hurricanes. The eye pressure in Katrina fell to 90.2 kPa (902 millibars), making it the fourth most intense hurricane on record (after Gilbert 1988, the Labor Day storm 1935, and Allen 1980). This pressure was recorded at sea. When Katrina reached land, the central pressure was 91.8 kPa (918 mb), making Katrina the third most intense storm to make landfall in the United States (after the Labor Day storm 1935 and Camille 1969).

The monetary cost was predicted to be between $20 billion and $100 billion, making Katrina the most costly hurricane ever. The final death toll was 972 in Louisiana and 221 in Mississippi.

Keith A hurricane that struck Central America in 2000. On September 30, it killed one person in El Salvador, and the following day it struck Nicaragua, where a 16-year-old boy was swept away by a swollen river as the hurricane reached Category 3 on the SAFFIR/SIMPSON HURRICANE SCALE, with winds of 135 MPH (217 km/h). Keith then struck Belize and the Yucatán peninsula of Mexico, its winds dropping to 90 MPH (145 km/h). It weakened to a tropical storm as it moved out over the Gulf of Mexico, but then strengthened to category 2 as it headed back toward the Mexican coast. By the time it died, Keith had caused at least 12 deaths and had dropped 22 inches (559 mm) of rain on Belize.

Kelly A typhoon that struck the Philippines on July 1, 1981. It caused floods and landslides in which about 140 people died.

Khanun A typhoon that struck Zhejiang Province, China, on September 11, 2005, destroying more than 7,000 homes and killing at least 14 people.

Kina A cyclone, rated as category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Fiji on January 2 and 3, 1993. It generated winds of up to 115 MPH (185 km/h) and killed 12 people.

Kirk A typhoon that crossed southwestern Honshu, Japan, on August 14, 1996, bringing winds of 130 MPH (209 km/h) and up to 12 inches (300 mm) of rain. It returned to the northern part of the island on August 15, but by then it had weakened. From there it moved to northeastern China where it caused floods that inundated 845 villages along the Yellow River.

Kirogi A typhoon that struck the Philippines, Japan, and Taiwan in July 2000. Kirogi was closely followed by another typhoon, Kai Tak. Kirogi generated sustained winds of 89 MPH (143 km/h) and brought heavy rain. Between them, the two typhoons killed 42 people in the Philippines, five in Japan, and one in Taiwan.

Kyle A typhoon that struck Vietnam on November 23, 1993. It killed at least 45 people.

Larry A category 5 cyclone that struck the coast of Queensland, Australia, on March 20, 2006, with winds of 180 MPH (290 km/h). The storm made landfall at Innisfail, about 60 miles (100 km) south of Cairns, uprooting trees, destroying sugar and banana crops, and wrecking homes, leaving thousands homeless.

Lenny A hurricane that struck islands in the Caribbean in November 1999. It was upgraded from a tropical storm on November 14, passed to the south of Jamaica with winds of 100 MPH (160 km/h), and its wind speeds increased to 125 MPH (201 km/h) on November 17. The following day its winds increased to 150 MPH (241 km/h) as it struck St. Croix in the U.S. Virgin Islands, where the storm continued for 12 hours. Other islands in the region also suffered, and a total of 13 people were killed. On November 19, it was downgraded to a tropical storm.

Lili A hurricane that struck the Caribbean and Louisiana in late September and early October 2002. The storm caused seven deaths and widespread damage in Jamaica and St. Vincent, and tore roofs from buildings in the Cayman Islands. It made landfall in Louisiana on October 2, with winds of 90 MPH (145 km/h).

Linda A typhoon that struck southern Vietnam, Cambodia, and Thailand in November 1997, destroying thousands of homes and sinking hundreds of fishing vessels. It killed 464 people in Vietnam and more than 20 in Cambodia and Thailand.

Linfa A tropical storm that struck Luzon, Philippines, on May 27, 2003, bringing torrential rain. At least 25 people were killed.

Lingling A tropical storm that struck the Philippines on November 7, 2001, with winds up to 56 MPH (90 km/h). It killed at least 68 people.

Liza A hurricane, rated category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck La Paz, Mexico, on October 1, 1976, killing at least 630 people and leaving tens of thousands homeless. It brought winds of 130 MPH (160 km/h) and 5.5 inches (140 mm) of rain. This destroyed an earth dam 30 feet (9 m) high, sending a wall of water 5 feet (1.5 m) high through a shantytown.

Longwan A typhoon that struck Fujian Province, China, causing floods that swept away a military school at Fuzhou on October 2, 2005, killing at least 80 people.

Luis A hurricane, rated as category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Puerto Rico and the U.S. Virgin Islands from September 4 to 6, 1995. Its winds gusted to more than 140 MPH (225 km/h). At least 15 people were killed. Luis was shortly followed by Marilyn.

Lynn A typhoon that struck Taiwan on October 24, 1987, and destroyed 200 homes.

Maemi A typhoon that struck South Korea on September 12, 2003. It was said to have been the worst storm to strike the country for 100 years. Maemi caused severe damage to the port of Pusan and killed at least 124 people.

Maria A typhoon that struck the southern Chinese provinces of Guangdong and Hunan on September 1, 2000. A cargo ship sank in Shanwei harbor, more than 7,000 homes were damaged, and at least 45 people were killed. The cost of the damage was estimated at $223 million.

Marilyn A hurricane that struck the U.S. Virgin Islands and Puerto Rico on September 15 and 16, 1995, not long after Luis. It generated winds of more than 100 MPH (160 km/h) and destroyed 80 percent of the houses on St. Thomas. It killed nine people.

Martin A cyclone that struck the Cook Islands in November 1997. It killed nine people.

Maury A typhoon that struck northern Taiwan on July 19, 1981. It caused floods and landslides in which 26 people died.

Meli A cyclone that struck Fiji on March 27, 1979. It killed at least 50 people and destroyed about 1,000 homes.

Mike A typhoon that struck the Philippines on November 14, 1990. It killed 190 people and rendered 120,000 homeless.

Mindulle A typhoon that struck Luzon, Philippines, on June 29, 2004, where it killed 31 people. It then moved on to Taiwan, where on July 1 it killed 15 people.

Mireille A typhoon, rated as category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Kyushu and Hokkaido, Japan, on September 27, 1991. It generated winds of up to 133 MPH (214 km/h) and killed 45 people.

Mitch A hurricane, which weakened to a tropical storm, that struck Central America in late October 1998. It formed on October 21 in the southwest Caribbean, then moved toward Honduras and intensified to category 5 hurricane status on the SAFFIR/SIMPSON HURRICANE SCALE. On October 29, it was downgraded to a tropical storm and moved inland and southward. The storm was declared over on November 1. The high rainfall associated with it caused appalling damage from flooding, in which an estimated 11,000 people died, the highest death toll from a hurricane for 200 years. During a period of 41 hours, from 3 P.M. on October 29 to 7 A.M. on October 31, a total of 27.5 inches (698 mm) of rain fell on Honduras, and between 6 P.M. on October 27 and 9 P.M. on October 31 the rainfall was 35.3 inches (896 mm).

Muroto II A typhoon that struck Japan in September 1961. It caused a STORM SURGE of 13 feet (3.9 m) that produced floods in Osaka in which 32 people died.

Nabi A typhoon that struck southern Japan on September 6, 2005. Approximately 250,000 people had to be evacuated, and at least 18 were killed.

Namu A typhoon that struck the Solomon Islands on May 19, 1986. It killed more than 100 people and rendered more than 90,000 homeless.

Nanmadol A typhoon that struck the Philippines in December 2004, during the cleanup following typhoon Winnie. After the two storms had passed, at least 1,000 persons were dead or missing.

Nari A typhoon that struck Taiwan from September 16 to 19, 2001. It caused floods, mudslides, and extensive damage, killing at least 94 people.

Nell A typhoon that struck the Philippines on December 25 and 26, 1993. It killed at least 47 people.

Nina A typhoon that struck the Philippines on November 26, 1987, and caused a STORM SURGE. It killed 500 people in Sorsogon Province, Luzon.

Ofelia A typhoon that struck the Philippines, Taiwan, and China on June 23 and 24, 1990. It killed a total of 57 people.

Olga A typhoon that struck Luzon, Philippines, in May 1976. It brought rains so heavy that they caused widespread flooding in which 215 people died and at least 600,000 were rendered homeless. The floods caused $150 million of damage.

Olga is also a category 1 typhoon on the SAFFIR/SIMPSON HURRICANE SCALE that struck Japan and South Korea on August 2 and 3, 1999. In Japan it brought 23 inches (584 mm) of rain to the area around Kochi and up to 1 inch (25 mm) of rain an hour to other places. One woman died when she was crushed by a landslide caused by the heavy rain. The heavy rain in South Korea caused 29 deaths and left 22 people missing. It destroyed more than 74,000 acres (30,000 ha) of farmland, more than 8,000 homes, and left nearly 20,000 people homeless.

Olivia A hurricane that struck Mazatlán, Mexico, on October 24, 1975. It killed 29 people.

Opal A hurricane, rated as category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that formed over the Yucatán Peninsula, Mexico, on September 27, 1995. A few days later, it weakened to a tropical storm, but by October 2 had strengthened and was once again classed as a hurricane. By the time it reached Florida, on October 4, it had weakened to category 3. From Florida it moved into North Carolina, Georgia, and Alabama. Most of the damage it caused, estimated at more than $2 billion, was due to a STORM SURGE that produced breaking waves and waves 12 feet (3.6 m) high. Opal killed 50 people in Guatemala and Mexico and 13 in the United States.

Orchid A typhoon that struck South Korea on September 11, 1980. It killed seven people, and more than 100 fishermen were lost at sea.

Pat A typhoon, rated category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Kyushu, Japan, on August 30, 1985. It generated winds of up to 124 MPH (200 km/h) and killed 15 people.

Paul A hurricane, rated category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Sinaloa, Mexico, on September 30, 1982. It generated winds of 120 MPH (193 km/h) and left 50,000 people homeless.

Pauline A hurricane that struck southern Mexico from October 8 to 10, 1997. It generated winds of up to 115 MPH (185 km/h) and waves up to 30 feet (9 m) high, and caused extensive damage in the city of Acapulco and in coastal villages in the states of Oaxaca and Guerrero. The hurricane killed 217 people and rendered 20,000 homeless.

Peggy A typhoon that struck the northern Philippines on July 9, 1986. It caused floods, landslides, and mudslides, bringing extensive damage to property. More than 70 people were killed. It then moved to southeastern China, where it arrived on July 11 and caused widespread flooding. More than 170 people were killed, at least 1,250 injured, and more than 250,000 homes were destroyed.

Phyllis A typhoon that struck the Japanese island of Shikoku in August 1975. It killed 68 people. A week later, the island was struck by Typhoon Rita.

Polly A tropical storm that caused a STORM SURGE with waves 20 feet (6 m) high on August 30 and 31, 1992, at Tianjin, China. It killed 165 people along the southeastern coast and rendered more than 5 million homeless.

Pongsona A category 4 typhoon that struck Guam and the Mariana Islands on December 9, 2002, with winds of up to 150 MPH (240 km/h).

Rananim A typhoon that made landfall in Zhejiang Province, China, on August 12, 2004, then moved inland, killing at least 164 people. It was the most powerful typhoon to strike China in seven years.

Rex A typhoon that struck northern Japan in August 1998. It caused floods and landslides in which at least 11 people died, and 40,000 were forced to evacuate their homes.

Rita Two typhoons and one hurricane, the first of which struck the Japanese island of Shikoku in August 1975, one week after Typhoon Phyllis. Rita killed 26 people and injured 52.

The second typhoon Rita, rated category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, struck the Philippines on October 26, 1978. Nearly 200 people were killed, and about 10,000 homes were destroyed.

Hurricane Rita struck Louisiana on September 23, 2005, breaching levees at New Orleans that had recently been repaired following hurricane Katrina, and flooding parts of the city once more. Rita reached the Gulf Coast on September 24, making landfall close to the Texas–Louisiana border, but causing little damage and few injuries.

Roxanne A hurricane, rated at category 3 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck the island of Cozumel, off the Mexican coast, in October 1995, generating winds of 115 MPH (185 km/h). It killed 14 people, and tens of thousands were forced to flee their homes.

Ruby A typhoon that struck the Philippines on October 24 and 25, 1988. It caused floods and landslides in which about 500 people died. The damage was estimated at $52 million.

Rumbia A tropical storm that struck southern Mindanao, Philippines, on November 30, 2000. It brought heavy rain and high waves that caused flooding. More than 1,600 people were forced to leave their homes.

Rusa A typhoon that struck South Korea on August 31 and September 1, 2002, with winds of up to 124 MPH (200 km/h). It killed more than 180 people and caused damage costing more than $1 billion.

Ruth Two typhoons, the first of which struck Vietnam on September 15, 1980. It killed at least 164 people.

The second Typhoon Ruth, rated as category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, struck Luzon, Philippines, on October 27, 1991. It generated winds of up to 143 MPH (230 km/h) and killed 43 people.

Sally A typhoon that passed Hong Kong on September 10, 1996, then crossed the coast of Guangdong, China, bringing winds of up to 108 MPH (174 km/h). It killed more than 130 people and destroyed nearly 400,000 homes.

Sarah A typhoon that struck Taiwan on September 11, 1989. It broke a Panamanian-registered freighter in half and killed 13 people.

Skip A typhoon that struck the Philippines on November 7, 1988. High winds and heavy rain caused mudslides and floods in which at least 129 people died. It was the second typhoon to strike the Philippines in two weeks.

Stan A hurricane that made landfall on the Gulf Coast of Mexico on October 4, 2005, then moved through Central America. It caused floods and landslides that killed at least 71 people in El Salvador, at least 654 in Guatemala, and more than 60 in Nicaragua, Honduras, Mexico, and Costa Rica.

Steve A tropical cyclone that struck Cairns, Queensland, Australia, on February 27, 2000. It brought winds of 105 MPH (169 km/h). There were no reported injuries or deaths.

Sybil A tropical storm that struck the Philippines on October 1, 1995. It triggered floods, landslides, and volcanic mudflows, causing damage in 29 provinces and 27 cities. More than 100 people were killed.

Tad A typhoon, rated category 1 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck central and northern Japan on August 23, 1981, killing 40 people and leaving 20,000 homeless. It brought winds of up to 80 MPH (128 km/h).

Talim A typhoon that struck Anhui Province, China, on September 1, 2005, causing flooding and landslides, and killing 53 people.

Teresa A typhoon that struck Luzon, Philippines, on October 23, 1994. It killed 25 people.

Thelma Two typhoons, the first of which, rated category 4 on the SAFFIR/SIMPSON HURRICANE SCALE, struck Kaohsiung, Taiwan, on July 25, 1977. It generated winds of up to 120 MPH (193 km/h). Nearly 20,000 homes were destroyed and 31 people died.

The second Typhoon Thelma struck South Korea on July 15, 1987. It caused floods, landslides and mudslides in which at least 111 people died.

Tico A hurricane that struck the coast of Mazatlán, Mexico, on October 10, 1983. It killed 105 fishermen, whose boats were lost at sea.

Tip A typhoon that struck Japan on October 19, 1979, with winds of up to 55 MPH (88 km/h). At least 36 people died. On October 12, surface pressure in the eye of Tip was 870 mb; this is the lowest surface pressure ever recorded.

Tokagi A typhoon that struck Japan on October 30, 2004, killing at least 83 people.

Toraji A typhoon that struck Hualien and Nantou Provinces, Taiwan, on July 30, 2001. It caused floods and landslides in which 77 people died and 133 were missing and presumed dead.

Tracy A cyclone that struck Darwin, Australia, on December 25, 1974. It destroyed 90 percent of the city and killed more than 50 people.

Uma A cyclone that struck Vanuatu on February 7, 1987. It killed at least 45 people.

Utor A typhoon that occurred in early July 2001. Utor killed one person in Taiwan, at least 121 people in the Philippines, and 23 in Guangdong Province, China.

Val A typhoon, rated as category 5 on the SAFFIR/SIMPSON HURRICANE SCALE, that struck Western Samoa from December 6 to 10, 1991. It generated winds of up to 150 MPH (241 km/h) and killed 12 people and rendered 4,000 homeless.

Vera Two typhoons, the first of which struck Honshu, Japan, in September 1959. It killed nearly 4,500 people, destroyed about 40,000 homes, and left 1.5 million people homeless.

The second Typhoon Vera struck Zhejiang Province, China, on September 16, 1989. It killed 162 people and injured 692.

Victor A typhoon that struck Guangdong and Fujian Provinces, China, in August 1997. It killed 49 people and destroyed 10,000 homes.

Violet A typhoon that crossed Japan on September 22, 1996, with winds of 78 MPH (125 km/h). It killed at least seven people, most of them in the Tokyo area, and caused about 200 landslides in Honshu, where it destroyed more than 80 homes and flooded more than 3,000. By the following day, as it moved out into the Pacific, Violet had weakened to a tropical storm.

Wally A cyclone that struck Fiji in April 1980. It caused floods and landslides in which at least 13 people died and thousands were left homeless.

Willie A typhoon that struck the island of Hainan, China, in September 1996. It caused floods that affected 70 percent of the streets of the capital, Haikou, and inundated 95,000 acres (38,000 ha) of farmland. At least 38 people were killed.

Wilma A category 4 hurricane that crossed the Caribbean in October 2005, producing winds of up to 150 MPH (240 km/h). It killed 13 people in Haiti and Jamaica before making landfall on the Mexican coast on October 21. Wilma then remained stationary for a full day, devastating Cancún, Cozumel, and Playa del Carmen and killing 6 people. On October 24 Wilma crossed Florida, killing 22 people. The core pressure of Wilma fell to 882 mb, making this the strongest hurricane ever recorded, with a lower pressure than that of Gilbert in 1988 (though not so low as that of typhoon Tip).

Winnie A typhoon that struck Taiwan, eastern China, and the Philippines on August 18 and 19, 1997. It generated winds of up to 92 MPH (148 km/h) and caused widespread flooding, especially in Taiwan and the Philippines. At least 37 people were killed in Taiwan, 140 in the Chinese provinces of Zhejiang and Jiangsu, and 16 in the Philippines. Tens of thousands of homes were destroyed in China, and in the Philippines 60,000 people were forced to leave their homes.

A second typhoon Winnie struck the Philippines on November 29, 2004, closely followed by typhoon Nanmadol. After the two storms had passed, at least 1,000 persons were dead or missing.

Wukong A typhoon that struck southern China on the weekend of September 9–10, 2000. Five people were killed, more than 1,000 houses collapsed, and 49,420 acres (30,710 ha) of rubber trees, bananas, rice, and pepper plants were destroyed.

Xangsane A typhoon that struck Taiwan on November 1 and 2, 2000. It brought winds of 90 MPH (145 km/h) and severe flooding. A Panamanian cargo ship, the *Spirit of Manila,* sank in the storm after breaking into three pieces. The storm killed 58 people, and 31 were missing, including 23 of the crew of the *Spirit of Manila*. Xangsane (pronounced Chang*sharn*) caused more than $2 billion of damage to crops and farms. The name means "elephant" in Thai.

Yancy Two typhoons, the first of which struck the Philippines and China in August 1990. It killed 12 people in the Philippines and 216 people in Fujian and Zhejiang Provinces, China.

The second Typhoon Yancy struck Kyushu, Japan, in September 1993. Rated category 4 on the SAFFIR/

Simpson hurricane scale, it generated winds of up to 130 MPH (209 km/h) and killed 41 people.

Yanni A tropical storm that struck South Korea in late September and early October 1998. It flooded about one-quarter of the country's cropland and caused the deaths of at least 27 people.

York A typhoon that struck Hong Kong on September 16, 1999, crossing the territory and reaching Guangzhou, in mainland China, later the same day. The maximum wind speed was 93 MPH (150 km/h). York brought heavy rain to the province of Fujian. At least one person was killed in Hong Kong and six in Fujian.

Zack A tropical storm that struck the Philippines in October 1995. It capsized a ship sailing between islands, killing 59 people. It caused severe flooding on land. A total of at least 100 people died, and 60,000 were forced to leave their homes.

Zane A typhoon that crossed Taiwan on September 28, 1996. It triggered mudslides and killed two people, then moved away to Okinawa.

Zeb A typhoon that struck the Philippines, Taiwan, and Japan in October 1998. It killed at least 74 people in the Philippines, 25 in Taiwan, and 12 in Japan.

Zoe A category 5 cyclone that struck the Solomon Islands on December 28, 2002, with winds of up to 220 MPH (350 km/h). It caused widespread devastation on the islands of Tikopia and Anuta.

Appendix III
Chronology of Tornadoes

Many tornadoes occur in remote areas, far from human habitations, but if they strike in populated areas, they can cause great devastation.

1140: Warwickshire, England. Extensive damage.

July 1558: Nottingham, England. Extensive damage and some deaths.

October 1638: Devon, England. Between five and 50 deaths.

May 1840: Natchez, Mississippi. 317 killed.

June 1865: Viroqua, Wisconsin. More than 20 killed.

December 1879: Scotland. The Tay Bridge destroyed by two tornadoes that struck simultaneously. Between 75 and 90 killed.

February 1884: Mississippi, Alabama, North Carolina, South Carolina, Tennessee, Kentucky, Indiana. More than 800 killed.

May 1896: Missouri and Illinois. 300 killed.

June 1899: New Richmond, Wisconsin. 117 killed, at least 150 injured.

May 1902: Goliad, Texas. 114 killed.

March 1925: Missouri, Illinois, and Indiana. 689 killed by up to seven tornadoes. A separate tornado at Annapolis, Maryland, overturned passenger trains and lifted 50 motorcars, carried them over houses, and dropped them in fields.

March 1932: Alabama. 268 killed.

April 1936: 216 killed at Tupelo, Mississippi, and 203 at Gainesville, Georgia, by two separate tornadoes.

June 1944: Ohio, Pennsylvania, West Virginia, and Maryland. 150 killed.

April 1947: Texas, Oklahoma, and Kansas. 169 killed.

March 1952: Arkansas, Missouri, and Texas. 208 killed.

May 1953: Texas. 114 killed.

June 1953: 143 killed in Michigan and Ohio and 90 around Worcester, Massachusetts, by two separate tornadoes.

May 1955: Kansas, Missouri, Oklahoma, and Texas. 115 killed.

April 1965: Indiana, Illinois, Ohio, Michigan, and Wisconsin. 271 killed.

February 1971: Mississippi Delta. 110 killed.

January 1973: San Justo, Argentina. 60 killed.

April 1974: More than 300 killed during the super outbreak.

June 1974: Oklahoma, Kansas, and Arkansas. 24 killed by several tornadoes.

January 1975: Mississippi. 12 killed, 200 injured when a tornado struck a shopping mall.

April 1976: Bangladesh. 19 killed, more than 200 injured.

April 1977: Bangladesh. More than 600 killed, 1,500 injured.

May 1977: Moundou, Chad. 13 killed, 100 injured.

March 1978: Delhi, India. 32 killed, 700 injured.

April 1978: Orissa State, India. Nearly 500 killed, more than 1,000 injured. 100 believed killed in West Bengal by another tornado.

April 1979: Texas and Oklahoma. 59 killed, 800 injured.

August 1979: Irish Sea. 18 killed when tornadoes struck yachts taking part in the Fastnet Race between England and Ireland.

May 1980: Kalamazoo, Michigan. Five killed, at least 65 injured.

April 1981: Bangladesh. About 70 killed, 1,500 injured. Orissa State, India. More than 120 killed.

April 1982: Kansas, Oklahoma, and Texas. Seven killed.

May 1982: Marion, Illinois. 10 killed.

April 1983: Fujian Province, China. 54 killed.

April 1983: Bangledesh. 12 killed, 200 injured.

May 1983: Texas, Tennessee, Missouri, Georgia, Louisiana, Mississippi, and Kentucky. 24 killed by at least 59 tornadoes.

May 1983: Vietnam. 76 killed.

March 1984: North and South Carolina. More than 70 killed.

April 1984: Water Valley, Mississippi. 15 killed. Oklahoma. 14 killed. Kentucky, Louisiana, Tennessee, Ohio, Maryland, and West Virginia. 14 killed.

June 1984: Russia. Hundreds killed.

October 1984: Maravilha, Brazil. 10 killed.

May 1985: Ohio, Pennsylvania, New York, and Ontario. 90 killed.

May 1987: Saragosa, Texas. 29 killed.

July 1987: Heilongjiang Province, China. 16 killed, more than 400 injured.

July 1987: Edmonton, Alberta, Canada. 25 killed.

April 1989: Bangladesh. Up to 1,000 killed, 12,000 injured.

May 1989: Texas, Virginia, North Carolina, Louisiana, South Carolina, and Oklahoma. 23 killed, more than 100 injured.

November 1989: Huntsville, Alabama. 18 killed.

June 1990: Indiana, Illinois, and Wisconsin. 13 killed.

May 1991: Bangladesh. 13 killed.

January 1993: Bangladesh. 32 killed, more than 1,000 injured.

April 1993: West Bengal, India. 100 killed.

March 1994: Alabama, Georgia, and North and South Carolina. 42 killed.

May 1996: Bangladesh. More than 440 killed, more than 32,000 injured.

March 1997: Arkansas. 25 killed.

May 1997: Central Texas. 30 killed, 24 in Jarrell.

July 1997: Kiangsu Province, China. 21 killed, more than 200 injured.

July 1997: Southern Michigan. 16 killed, more than 100 injured.

October 1997: Bangladesh. 25 killed, thousands injured.

May 1999: Kansas, Oklahoma, Texas. 46 people killed and about 900 injured by more than 76 tornadoes, at least one classified F-5.

February 2000: Georgia. 18 killed, about 100 injured.

July 2000: Alberta, Canada. 10 killed when a tornado swept through a trailer park near Edmonton.

October 2000: Bognor Regis, England. Four people injured and hundreds of homes damaged.

December 2000: Tuscaloosa, Alabama.11 people killed.

February 2001: Mississippi. Five killed. Arkansas. One person killed.

May 2001: Ellicott, Colorado. 18 killed.

November 9–11, 2002: United States. Nearly 90 tornadoes along a storm front from Gulf of Mexico to the Great Lakes. 17 killed in Tennessee, 12 in Alabama, five in Ohio, one in Mississippi, one in Pennsylvania; more than 200 injured.

May 4–12, 2003: United States. More than 300 tornadoes sweep through the midwestern and southern United States. Hundreds of homes damaged, at least 42 people killed.

April 14, 2004: Northern Bangladesh. Thousands of homes destroyed, at least 66 people killed.

March 20, 2005: Northern Bangladesh. At least 56 people killed in Gaibandha district, thousands homeless.

November 6, 2005: United States. Southern Indiana and northern Kentucky. 24 people killed, most in a trailer park outside Evansville, Indiana.

January 2, 2006: Missouri. Three persons injured.

March 9–13, 2006: United States. Outbreak of at least 105 tornadoes sweeps across the south-central United States, killing at least 11 people. One tornado is rated F-5 on the Fujita tornado intensity scale. Two other persons are also killed: one in an automobile accident and the other in a fire caused by lightning. These deaths are due to the weather but not directly to the tornadoes. March 12 is the most active day, with 62 confirmed tornadoes and storms producing hailstones the size of softballs.

Appendix IV
Laws, Regulations, and International Agreements

Air Quality Act 1967 A United States federal law that empowers the Department of Health, Education and Welfare to define areas within which air quality should be controlled, to set ambient air standards, to specify the methods and technologies to be used to reduce AIR POLLUTION, and to prosecute offenders if local agencies fail to do so.

Clean Air Act A law designed to improve air quality that was passed in 1956 in the United Kingdom, and a law with the same name that was passed in 1963 in the United States.

The British legislation was drafted in response to the London smog incidents (*see* AIR POLLUTION INCIDENTS) and empowered local governments to designate "smokeless zones" in which it became an offense to emit black smoke. As the act was implemented over the succeeding years, this had the desired effect of eliminating the domestic burning of coal in most cities in favor of smokeless fuels such as coke. Industrial plants continued to burn coal, but were required to fit devices to remove the smoke.

The U.S. act was introduced in order to strengthen the provisions of the Air Quality Act of 1960, and it was subsequently revised in 1970, with amendments passed in 1977, 1987, and 1990. The Clean Air Act increased the powers of the Environmental Protection Agency, especially in stipulating the emissions permitted from particular industrial installations. This proved difficult in practice, because it would have forbidden any further industrial development in states where existing emissions exceeded the permitted limits. This difficulty was overcome by allowing companies to agree with the regulatory authority to accept stricter emission standards for one part of their operation in return for a relaxation in the standards for another part. This was called a "bubble policy." It increased the effectiveness of pollution control while reducing its cost.

Clean Development Mechanism A procedure that is included in the Kyoto Protocol under which countries and companies are permitted to offset their own carbon emissions by paying for a project in another country that would reduce carbon emissions.

Framework Convention on Climate Change A United Nations agreement that was reached at the United Nations Conference on Environment and Development held in Rio de Janeiro, Brazil, in June 1992 (and sometimes called the Rio Summit or the Earth Summit). The Framework Convention aims to address the issue of GLOBAL WARMING by seeking the agreement of national governments to promote relevant research and to reduce emissions of greenhouse gases (*see* GREENHOUSE EFFECT). Its most direct achievement is the Kyoto Protocol, which sets targets for reduced emissions.

Geneva Convention on Long-Range Transboundary Air Pollution A legally binding international agreement that was drafted by scientists after a link had been established between sulfur emissions in Europe and the acidification of Scandinavian lakes (*see* ACID DEPOSITION). The convention was drawn up under the auspices of the United Nations Economic Commission for Europe, was signed in Geneva, Switzerland, in 1979, and came into force in 1983. It lays down the general principles that form the basis for international cooperation to reduce the emission of air pollutants that drift across international frontiers and also establishes an institutional framework for research and the development and implementation of policy. The executive body issues an annual report. Since it came into force, eight protocols have been added to the convention. These are:

- The 1984 Protocol on Long-term Financing of the Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe
- The 1985 Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 percent
- The 1988 Protocol Concerning the Control of Nitrogen Oxides or their Transboundary Fluxes
- The 1991 Protocol Concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes
- The 1994 Protocol on Further Reduction of Sulphur Emissions
- The 1998 Protocol on Heavy Metals
- The 1998 Protocol on Persistent Organic Pollutants
- The 1999 Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone

Kyoto Protocol An international agreement that was drawn up in 1997 under the auspices of the United Nations to provide guidelines for the implementation of the United Nations Framework Convention on Climate Change. The protocol committed the industrialized nations to reducing their emissions of six greenhouse gases (*see* GREENHOUSE EFFECT) by an average of 5.2 percent (measured against their 1990 levels) by 2012. The European Union agreed to an 8 percent reduction, the United States to 7 percent, Japan to 6 percent, and 21 other countries to varying reductions. Less-developed countries were not required to make binding commitments.

The protocol was adopted by about 170 nations, but not the United States, at Bonn, Germany, on July 23, 2001. The 5.2 percent target was retained, but countries were permitted to offset their emission reductions by counting the absorption of carbon dioxide by forest planting, changes in forest management, and improved management of croplands and grassland. Nations emitting less than their target amounts were allowed to sell the surplus, up to a cap of 10 percent of their total emission entitlement, as credits to nations unable to meet their targets.

Montreal Protocol on Substances That Deplete the Ozone Layer An international agreement that was reached in 1987 under the auspices of the United Nations Environment Program. The protocol aims to reduce and eventually eliminate the release into the atmosphere of all man-made substances that deplete stratospheric ozone (*see* OZONE LAYER). The provisions made in the protocol for achieving this have been strengthened through amendments adopted in London in 1990, Copenhagen in 1992, Vienna in 1995, and Montreal in 1997.

Appendix V
The Geologic Timescale

Eon/Eonothem	Era/Erathem	Sub-era	Period/System	Epoch/Series	Began Ma
Phanerozoic		Quaternary	Pleistogene	Holocene	0.11
				Pleistocene	1.81
	Cenozoic	Tertiary	Neogene	Pliocene	5.3
				Miocene	23.3
			Paleogene	Oligocene	33.9
				Eocene	55.8
				Paleocene	65.5
	Mesozoic		Cretaceous	Late	99.6
				Early	145.5
			Jurassic	Late	161.2
				Middle	175.6
				Early	199.6
			Triassic	Late	228
				Middle	245
				Early	251
	Paleozoic	Upper	Permian	Late	260.4
				Middle	270.6
				Early	299
			Carboniferous	Pennsylvanian	318.1
				Mississipian	359.2
			Devonian	Late	385.3
				Middle	397.5
				Early	416
		Lower	Silurian	Late	422.9
				Early	443.7
			Ordovician	Late	460.9
				Middle	471.8
				Early	488.3
			Cambrian	Late	501
				Middle	513
				Early	542

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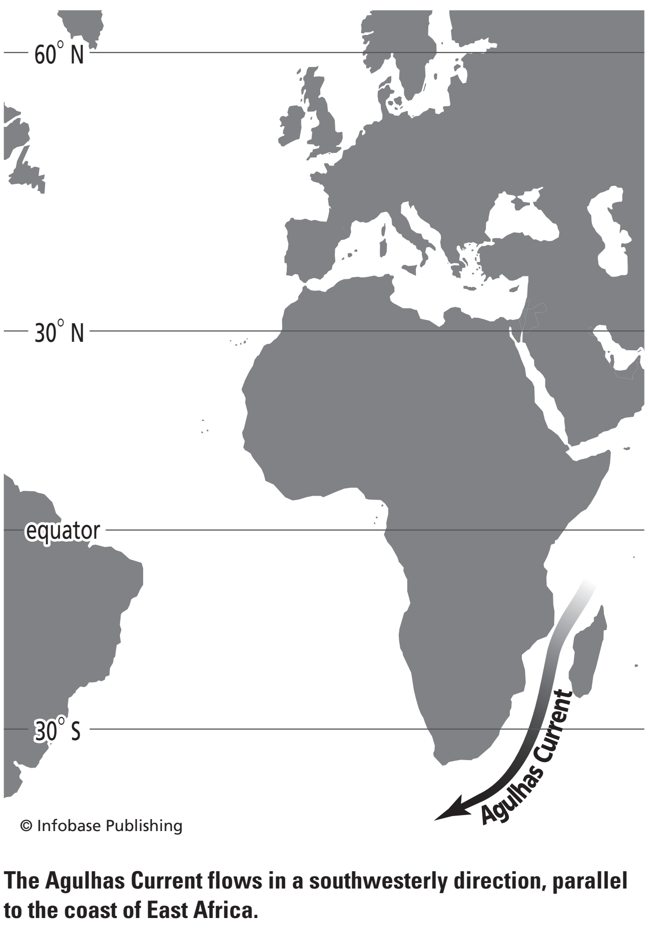
Eon/Eonothem	Era/Erathem	Sub-era	Period/System	Epoch/Series	Began Ma
Proterozoic	Neoproterozoic		Ediacaran		600
			Cryogenian		850
			Tonian		1,000
	Mesoproterozoic		Stenian		1,200
			Ectasian		1,400
			Calymmian		1,600
	Palaeoproterozoic		Statherian		1,800
			Orosirian		2,050
			Rhyacian		2,300
			Siderian		2,500
Archaean	Neoarchaean				2,800
	Mesoarchaean				3,200
	Palaeoarchaean				3,600
	Eoarchaean				3,800
Hadean	Swazian				3,900
	Basin Groups				4,000
	Cryptic				4,567.17

Source: International Union of Geological Sciences, 2004.

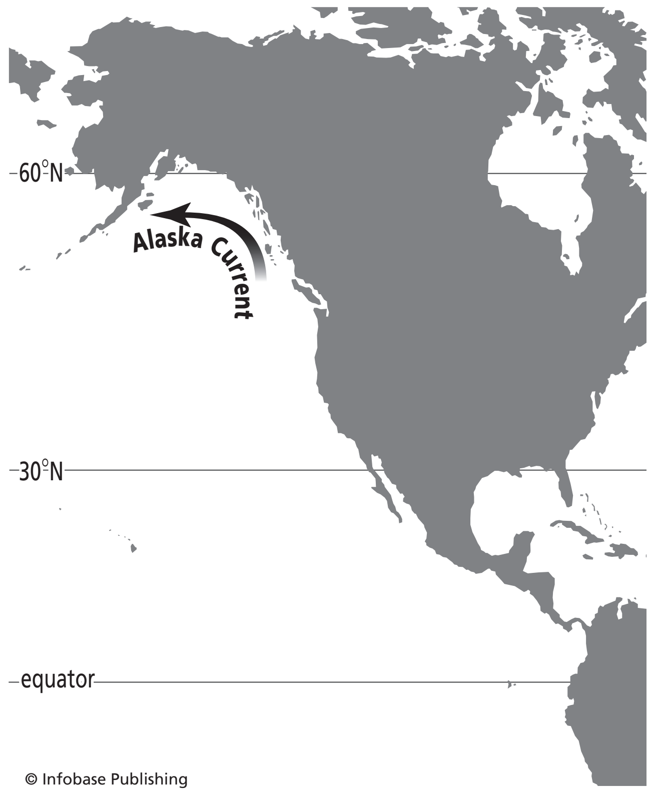
Note: Hadean is an informal name. The Hadean, Archaean, and Proterozoic Eons cover the time formerly known as the Precambrian. Tertiary has been abandoned as a formal name, and Quaternary is likely to be abandoned in the next few years, although both names are still widely used.

APPENDIX VI
OCEAN CURRENTS

Agulhas Current A current that flows in a southwesterly direction at the surface of the Indian Ocean, between the eastern coast of Africa and Madagascar, between latitudes 25°S and 40°S. Its speed is 0.7–2.0 feet per second (0.2–0.6 m/s).

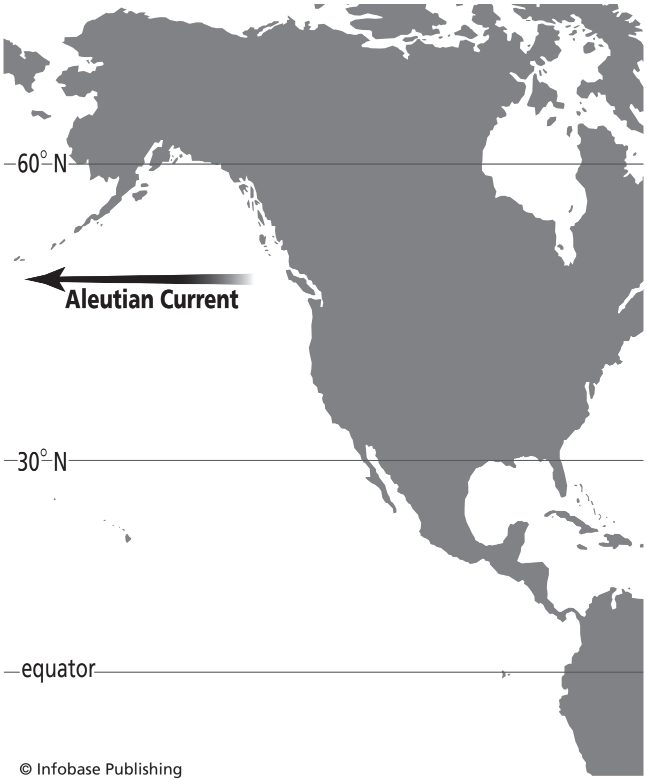


The Agulhas Current flows in a southwesterly direction, parallel to the coast of East Africa.



The Alaska Current is a branch of the North Pacific Current carrying warm water to the coasts of northwestern Canada and southeastern Alaska.

Alaska Current A warm ocean BOUNDARY CURRENT that flows northwestward and then westward along the coast of Canada and southeastern Alaska. It results from the deflection of the North Pacific Current as this current approaches the North American continent. It is sometimes called the Aleutian Current, although the two are usually regarded as distinct.



The Aleutian Current flows in a westerly direction to the south of the Aleutian Islands.

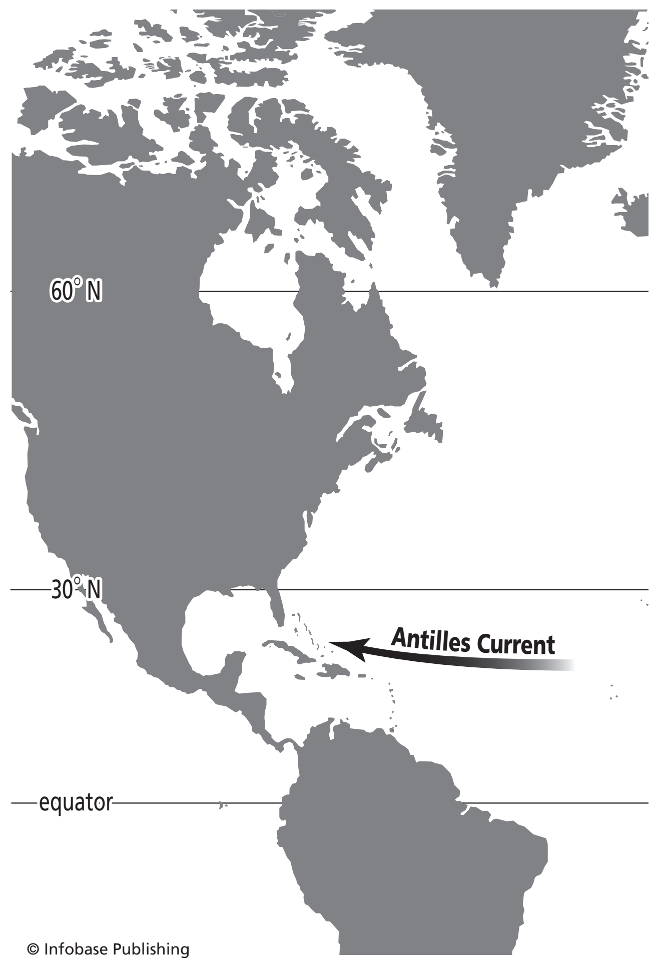
Aleutian Current (Sub-Arctic Current) A warm ocean current that flows in a westerly direction to the south of the Aleutian Islands. It runs parallel to the North Pacific Current, but to the north of it, and carries a mixture of warm water from the Kuroshio Current and cold water from the Oyashio Current. The Alaska Current is sometimes called the Aleutian Current, although the two are usually considered distinct.

Antarctic Circumpolar Current (West Wind Drift) An ocean current that flows from west to east around the coast of Antarctica. It is driven by the prevailing winds (see WIND SYSTEMS), which are from the west, and it is the only ocean current that flows all the way around the world. It carries water that is cold, with a temperature of 30–40°F (-1–+5°C), and has a low salinity, of less than 34.7 per mil. This current is not to be confused with the Antarctic Polar Current.

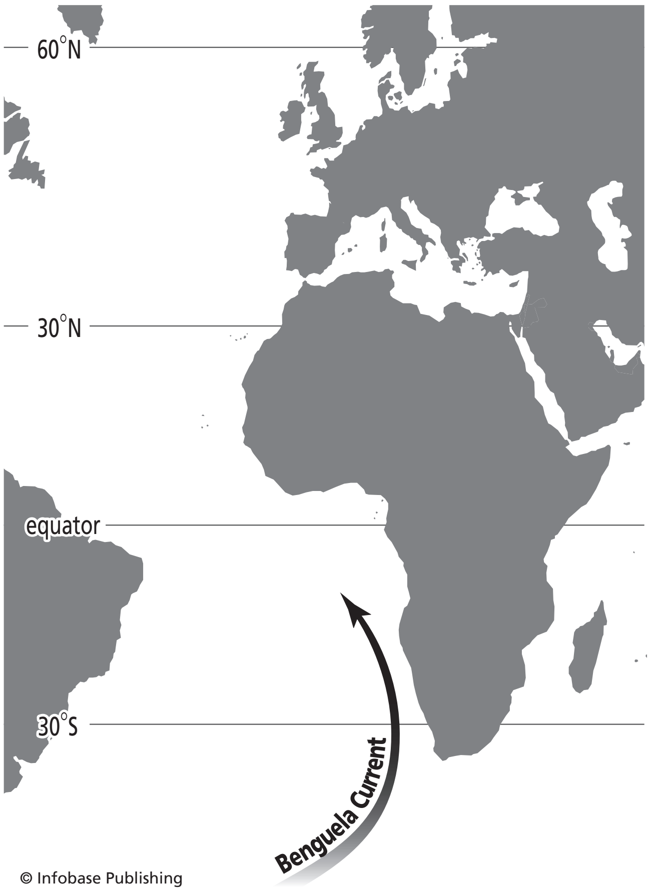
Antarctic Polar Current An ocean current that flows from east to west, parallel to the coast of Antarctica. It is driven by easterly winds that blow from off the ice cap. The current affects only surface waters. This current is not to be confused with the Antarctic Circumpolar Current, also known as the West Wind Drift.

Antilles Current An ocean current that branches from the North Equatorial Current and carries warm water along the northern coasts of the Great Antilles, in the Caribbean.

Benguela Current An ocean current that flows northward from the Antarctic Circumpolar Current and along the western coast of Africa, from about 35°S to 15°S. It carries cold water, with many UPWELLINGS, and flows fairly slowly, at less than 0.6 MPH (0.9 km/h).



The Antilles Current is a warm ocean current that flows past the Antilles, in the Caribbean.



The Benguela Current is a cold current flowing parallel to the coast of southern Africa.

Bering Current An ocean current that flows southward through the Bering Strait separating Alaska from eastern Siberia, bringing cold water into the North Pacific Ocean.

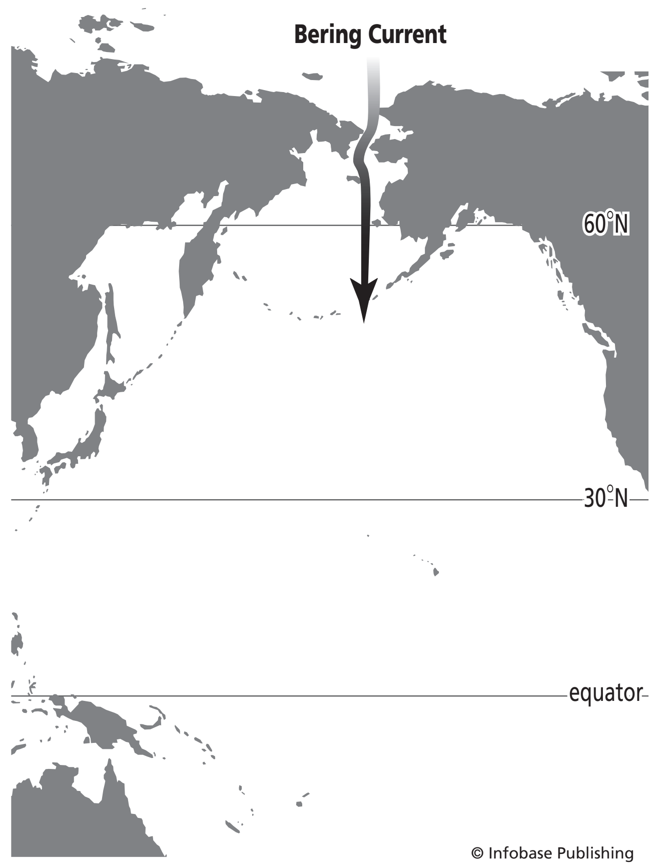
Brazil Current An ocean current that carries warm water southward from the South Equatorial Current, along the eastern coast of South America, to where it joins the Antarctic Circumpolar Current. The current moves very slowly, is no more than 330–660 feet (100–200 m) deep, and the salinity of its water is 36–37 per mil, which is saltier than the average for seawater.

California Current A slow-moving, somewhat diffuse ocean current that conveys cold water southward parallel to the western coast of North America. In the latitude of Central America, it turns westward to become the North Equatorial Current.

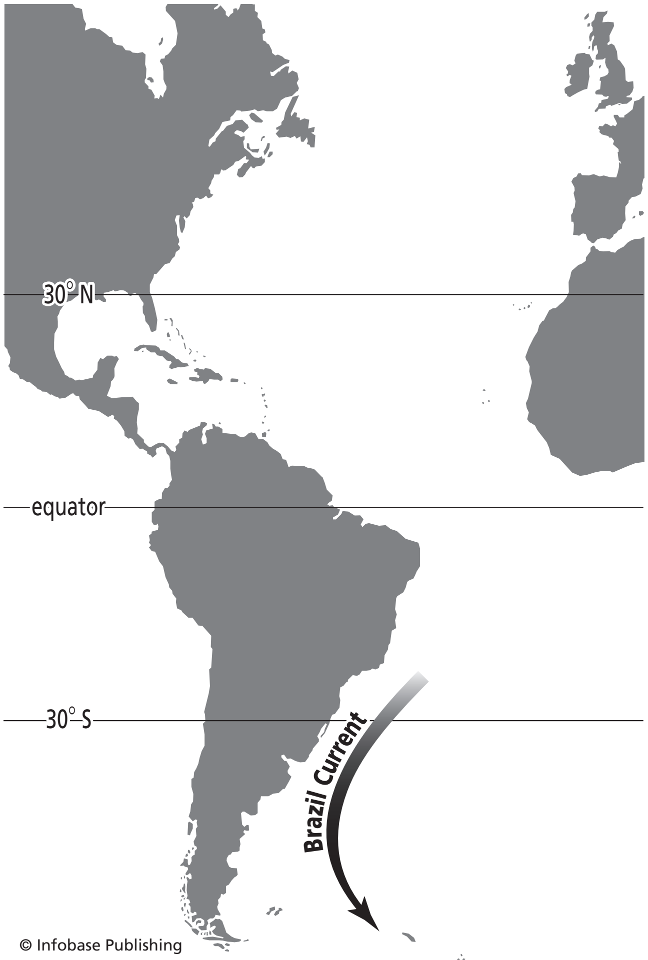
Canary Current A slow-moving ocean current that conveys cold water southward parallel to the coasts of Spain, Portugal, and West Africa. It is the cause of frequent sea FOGS off northwestern Spain and Portugal.

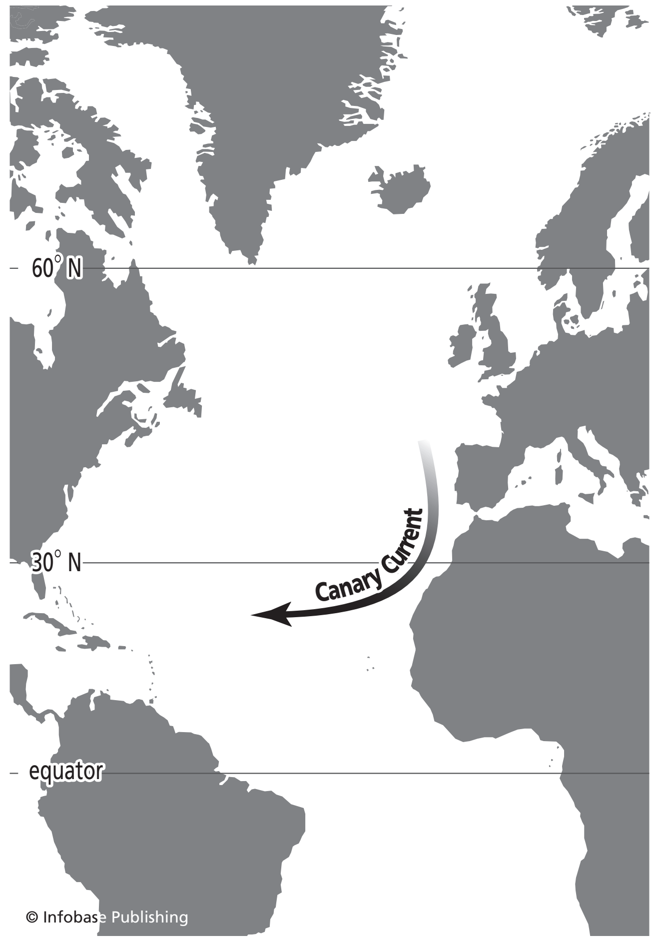
Caribbean Current An ocean current that flows westward through the Caribbean Sea. As it passes the coast of Florida, it joins the Florida Current, and it then becomes part of the Gulf Stream. The Caribbean Current carries warm water and flows at an average of 0.85–0.96 MPH (0.38–0.43 m/s).

Cromwell Current (Equatorial Undercurrent) An ocean current that flows from west to east beneath the



The Bering Current carries cold water from the Arctic into the North Pacific.


30° N
equator
30° S
Brazil Current
© Infobase Publishing


60° N
30° N
Canary Current
equator
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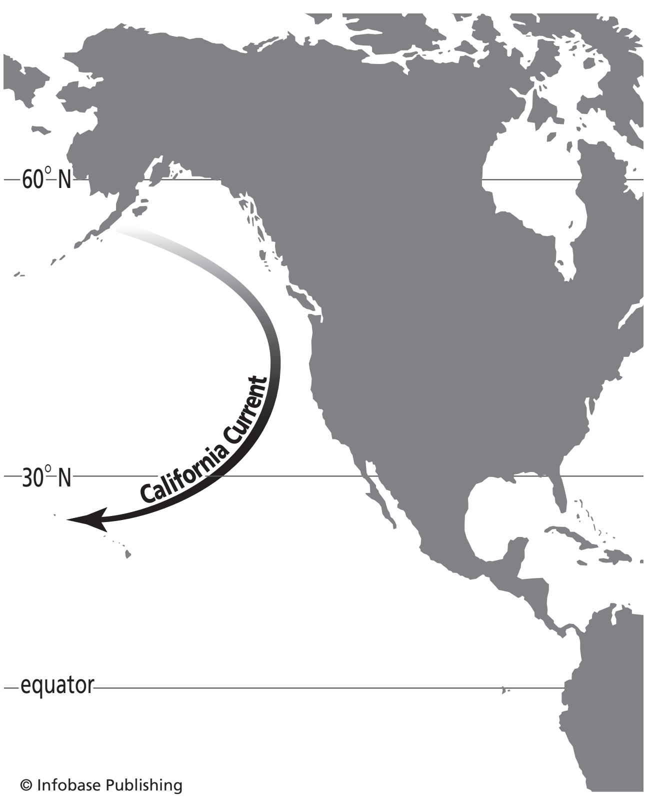
60° N
California Current
30° N
equator
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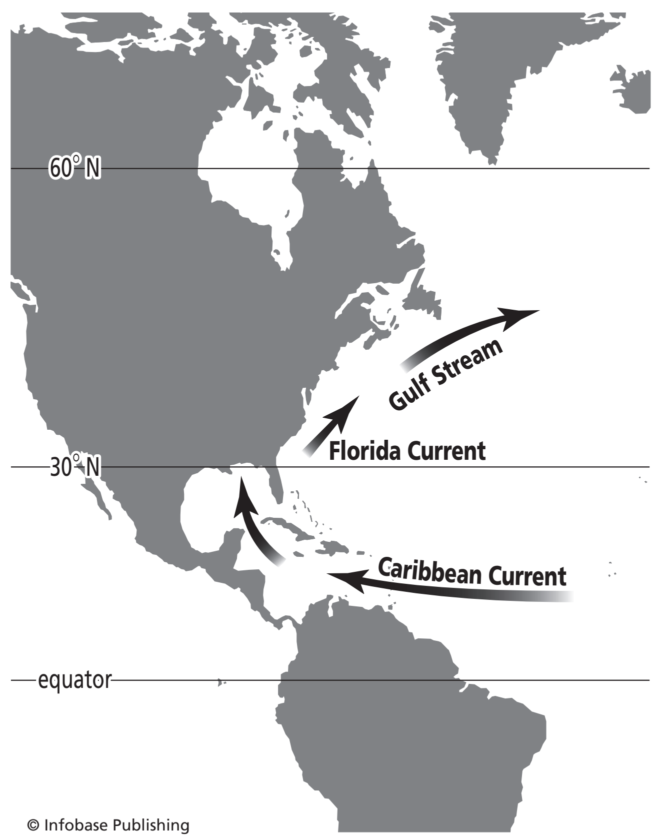
60° N
Gulf Stream
Florida Current
30° N
Caribbean Current
equator
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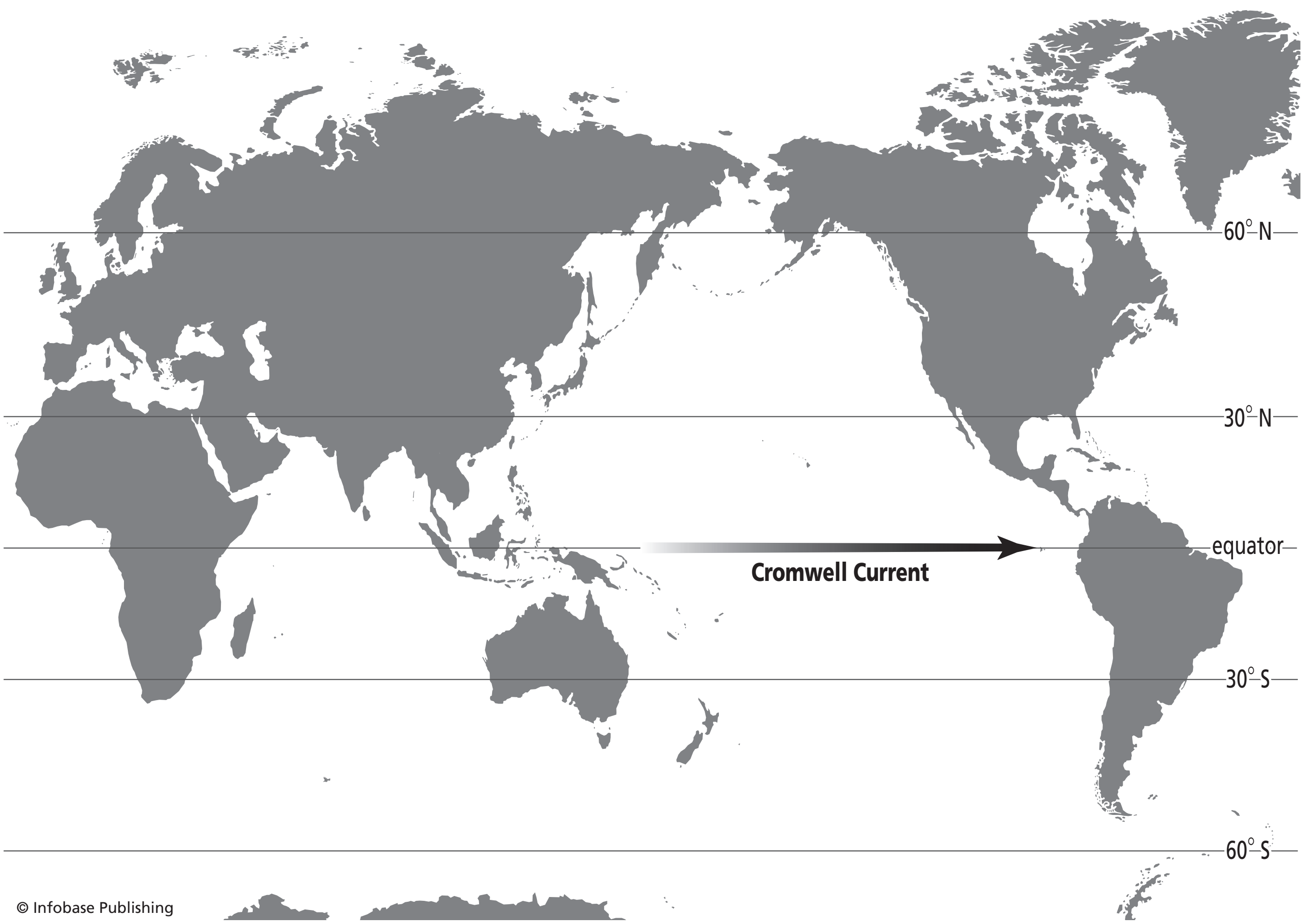
(Opposite page: Top left) **The Brazil Current is a warm current flowing parallel to the coast of Brazil.**
(Bottom left) **The California Current is a cold current flowing parallel to the coast of northwestern North America.**
(Top right) **The Canary Current is a cold current flowing parallel to the western coast of North Africa.**
(Bottom right) **The Caribbean Current flows westward through the Caribbean Sea, then joins the Florida Current before joining the Gulf Stream.**

surface of the Pacific Ocean between latitudes 1.5°N and 1.5°S and at a depth of 165–1,000 feet (50–300 m). The current is about 185 miles (300 km) wide and flows at up to 3.4 MPH (5.5 km/h). The surface Equatorial Current is driven by the trade winds (see WIND SYSTEMS) and carries warm surface water from east to west. The Cromwell Current counterbalances the Equatorial Current by conveying water below the surface in the opposite direction.

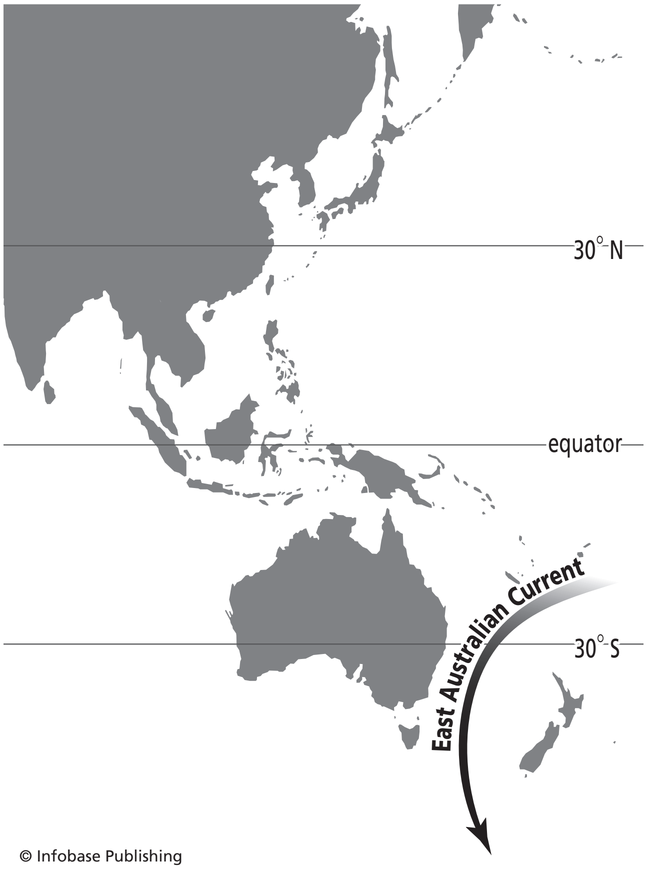
East Australian Current An ocean current that flows southward carrying warm water parallel to the eastern coast of Australia. The current is narrow, being only 330–660 feet (100–200 m) wide, and slow-moving, flowing at 0.6–1.2 MPH (1–2 km/h).

East Greenland Current An ocean current that flows southward from the Arctic Ocean into the North Atlantic Ocean, parallel to the northeastern coast of Greenland. In about the latitude of Iceland it merges with a branch of the North Atlantic Drift. The East Greenland Current carries cold water with a low salinity.

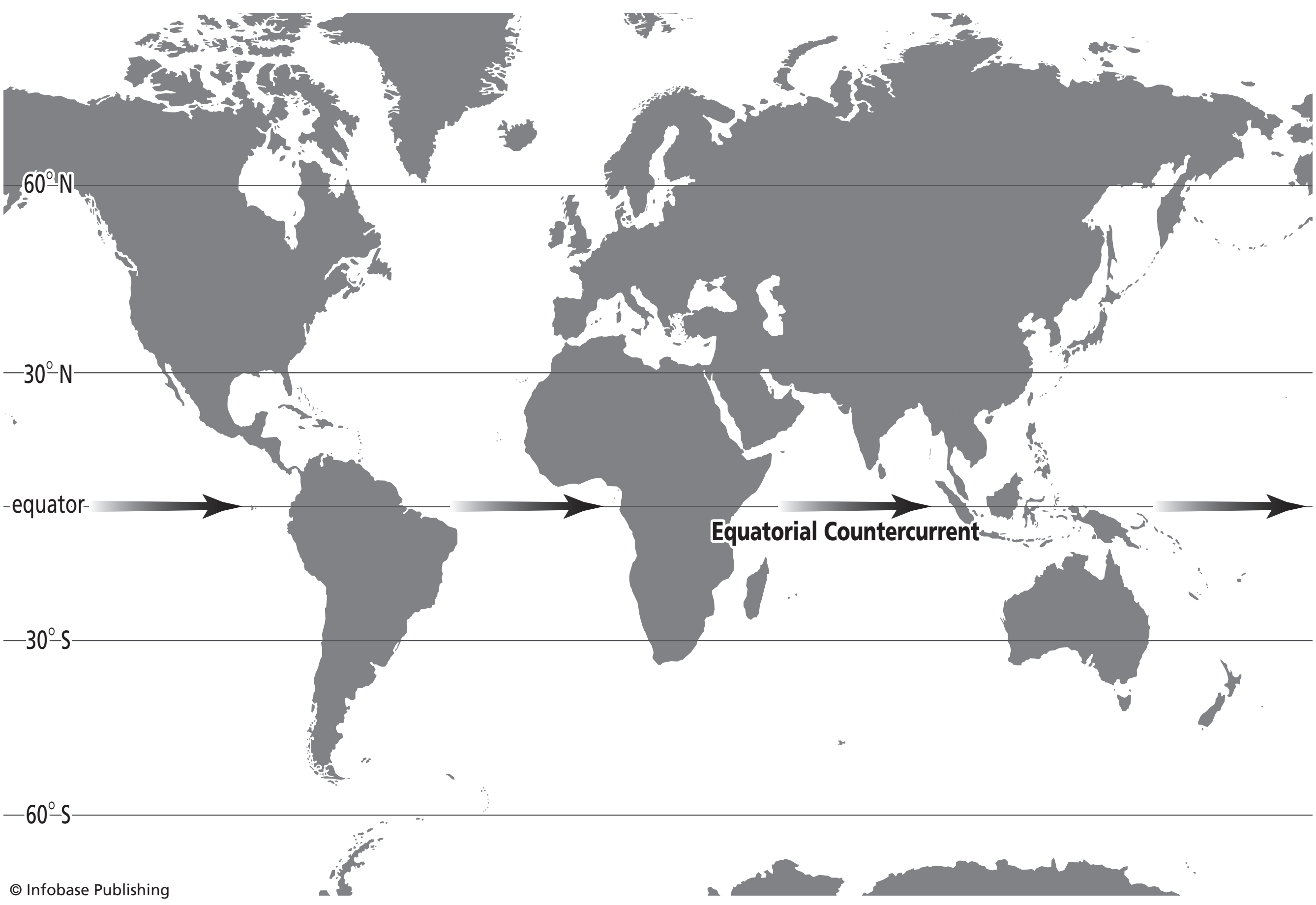
Equatorial Countercurrent A narrow ocean current that flows from west to east between the North and South Equatorial Currents.



The Cromwell Current is a wide, strong current flowing from west to east beneath the surface of the tropical Pacific.


30° N
equator
East Australian Current
30° S
© Infobase Publishing


East Greenland Current
60° N
30° N
© Infobase Publishing


60° N
30° N
equator
Equatorial Countercurrent
30° S
60° S
© Infobase Publishing

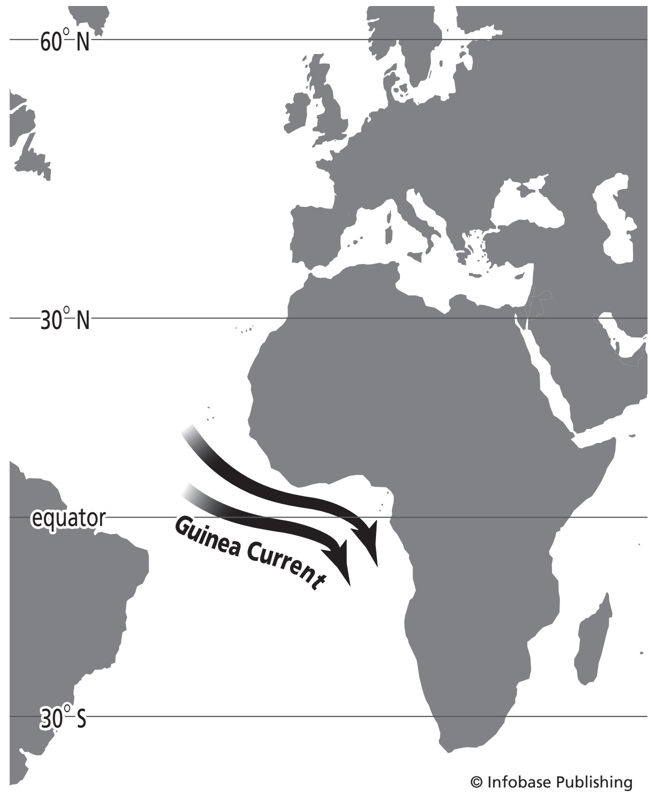
(Opposite page: Top left) **The East Australian Current is a warm current flowing parallel to the eastern coast of Australia.** ***(Opposite page: Top right)*** **The East Greenland Current is a cold current flowing parallel to the eastern coast of Greenland.** ***(Opposite page: Bottom)*** **The Equatorial Countercurrent flows close to the equator and from west to east in all oceans.**

Falkland Current An ocean BOUNDARY CURRENT that carries cold water northward past the Falkland Islands (Malvinas) and parallel to the coast of Argentina as far as about latitude 30°S and rather farther north in winter. Its influence greatly reduces the effect ordinarily produced by boundary currents outside the TROPICS, of bringing warm water to western coasts.

Florida Current An ocean current that flows northward parallel to the coast of Florida and that forms part of the Gulf Stream. It extends from the southern tip of Florida to Cape Hatteras, North Carolina. It is narrow, being 30–47 miles (50–75 km) wide, and fast, flowing at 2.2–6.7 MPH (3.6–11 km/h).

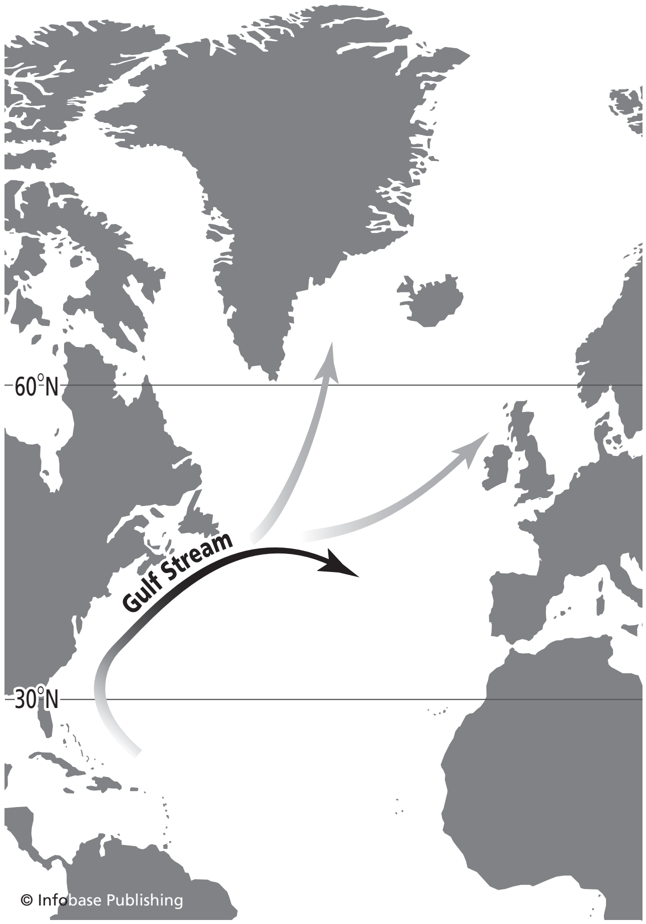
Guinea Current An ocean current that flows from west to east along the West African coast and into the Gulf of Guinea. It is part of the Equatorial Countercurrent and carries warm water with a temperature that often exceeds 80°F (27°C). The current brings hot, humid weather to coastal regions in the west, but farther east, off the coast of western Nigeria, the current produces UPWELLINGS. These frequently produce FOG and a fairly low rainfall of about 30 inches (762 mm) a year, compared with the 100 inches (2,540 mm) a year along the coast to the east of Lagos.

Gulf Stream A system of ocean currents that convey warm water from the Gulf of Mexico to the center of the North Atlantic Ocean. It begins as the Florida Current, where the North Equatorial Current enters the Gulf and ends in the latitude of Spain and Portugal,



The Guinea Current is a warm current flowing past the West African coast into the Gulf of Guinea.

The Falkland Current is a cold current flowing northward, parallel to the coast of Argentina.



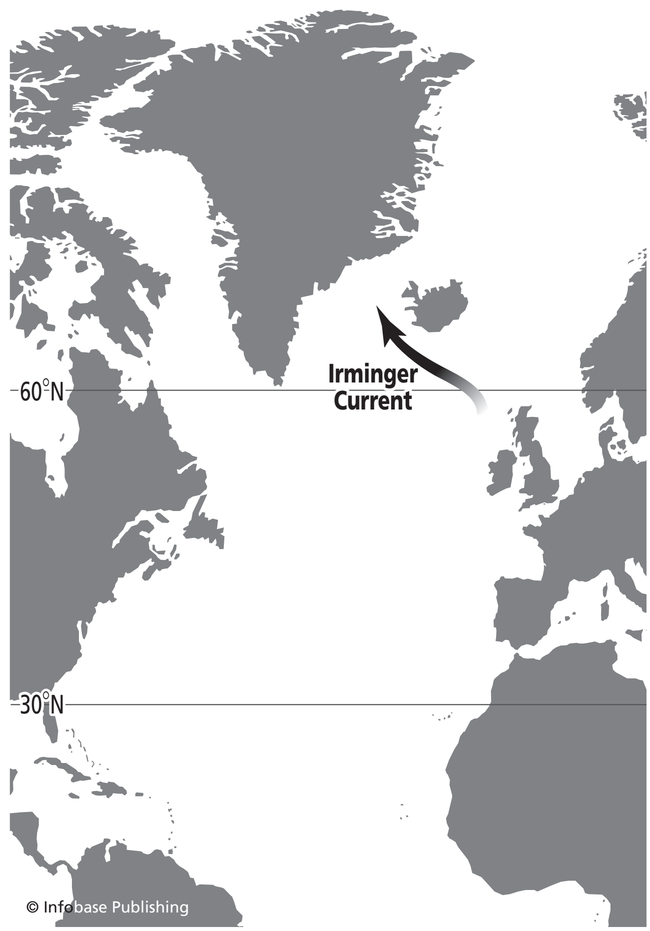
The Gulf Stream is a warm current that follows an approximately circular, clockwise path in the North Atlantic.

where it turns south, becoming the Canary Current and rejoining the North Equatorial Current. A branch from it becomes the North Atlantic Drift. Its influence on climates makes it the most important current system in the Northern Hemisphere. It is clearly defined, as a belt of water at a fairly constant temperature of 64–68°F (18–20°C) and salinity of 36 per mil.

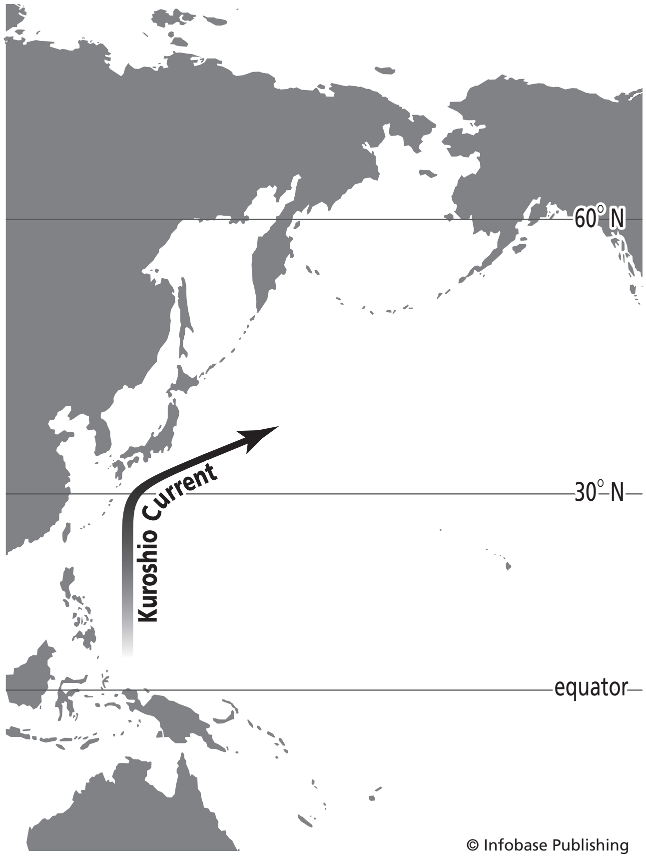
Irminger Current An ocean current that flows past the southern coast of Iceland and continues past the southern cape of Greenland. It is a branch of the Gulf Stream that breaks away from the North Atlantic Drift in about latitude 50°N and carries warm water northwestward. As it passes Greenland, its water mixes with cold water from Baffin Bay, but it can still be detected by its higher salinity as far as 65°N.

Kuroshio Current An ocean current that flows northward from the Philippines, along the coast of Japan, and then eastward into the North Pacific Ocean, carrying warm water northward. It is a narrow current, less than 50 miles (80 km) wide, and flows rapidly, at up to 7 MPH (11 km/h).

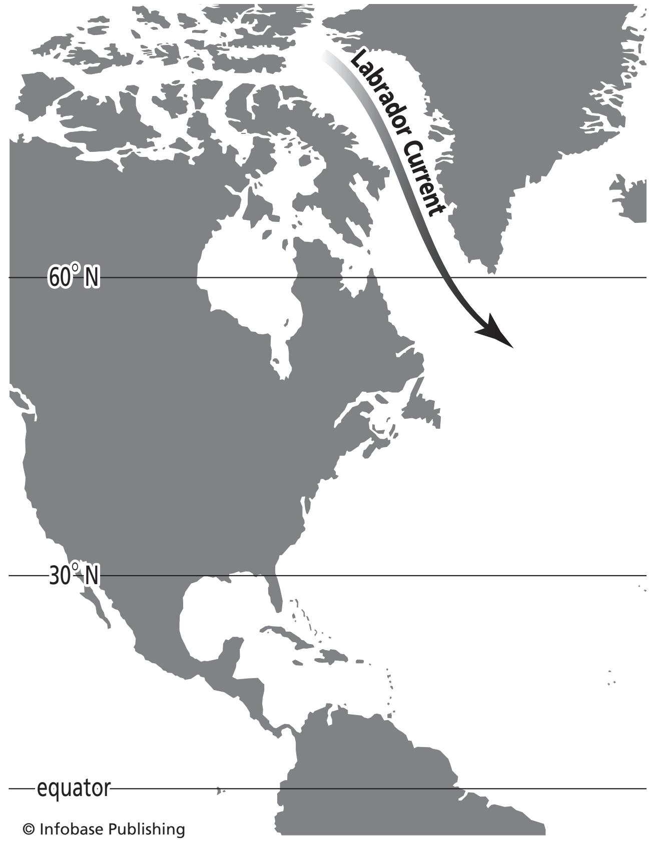
Labrador Current An ocean current that conveys cold water from the Arctic Ocean into the North Atlantic Ocean. It flows in a southeasterly direction between the coasts of eastern Canada and western Greenland, often carrying ICEBERGS south into the North Atlantic. Sea FOGS are common off Newfoundland, where the cold water of the Labrador Current meets the warm water of the Gulf Stream.



The Irminger Current breaks away from the Gulf Stream and flows past the southern coast of Iceland and Greenland.



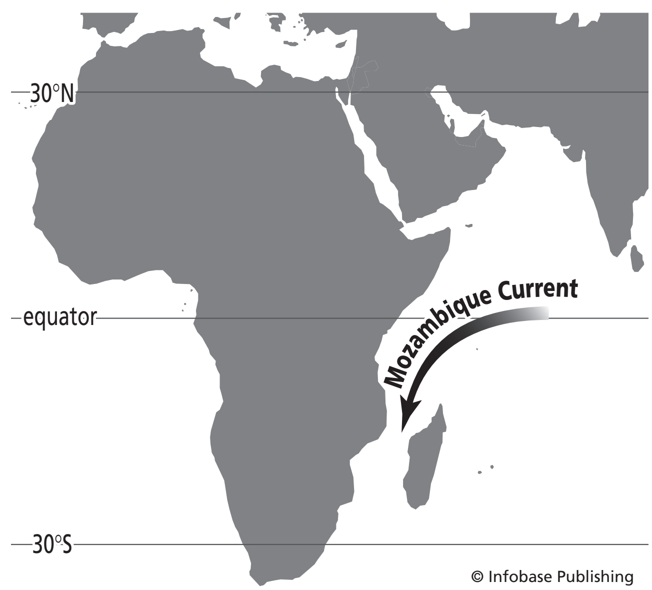
The Kuroshio Current is a warm current flowing parallel to the eastern coast of Japan.



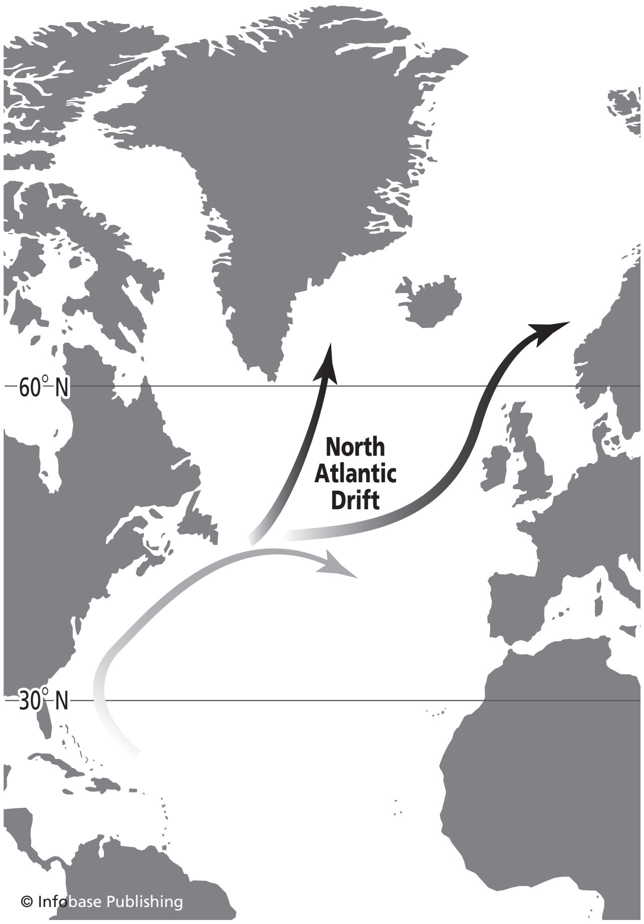
The Labrador Current is a cold current flowing parallel to the northeastern coast of Canada.

Monsoon Drift An ocean current that flows through the Arabian Sea. It breaks away from the North Equatorial Current off the southernmost tip of India, flows parallel to the western coast of India, then turns in about latitude 15–20°N to flow parallel to the southern coast of the Arabian Peninsula, finally joining the Somalia Current. This current flows past the eastern coast of Africa, through the Mozambique Channel separating Africa and Madagascar, and joins the Agulhas Current.

Mozambique Current A branch of the South Equatorial Current that flows around the northern end of Madagascar and continues as a warm ocean current in a southwesterly direction through the Mozambique Channel off the eastern coast of Africa. To the south of Madagascar, it becomes the Agulhas Current.



The Mozambique Current carries warm water into the Mozambique Channel, between Mozambique and Madagascar.



The North Atlantic Drift is a warm current that breaks away from the Gulf Stream to form two streams, one flowing to the east of Iceland and past the coasts of northwestern Europe, the other flowing to the west of Iceland toward Greenland.

North Atlantic Drift (North Atlantic Current) A broad, shallow, warm, surface current that is an extension of the Gulf Stream. It flows in a northeasterly direction from the middle of the North Atlantic Ocean and divides into two branches south of Iceland. The westerly branch flows northward and then turns south to join the East Greenland Current. The other branch passes to the east of Iceland in a northeasterly direction, approaching close to the coasts of the British Isles and continuing to become the Norwegian Current. The North Atlantic Drift exerts a strong influence on the climate of the coastal regions of northwestern Europe, making it milder and wetter than it would be otherwise.

North Equatorial Current Two ocean currents, one in the North Atlantic and the other in the North Pacific, that flow from east to west parallel to and just north of the equator. The current flows within the upper 1,600 feet (500 m) of water at a speed of 0.6–2.5 mph (1–4 km h^{-1}) and is separated from the South Equatorial Current by the Equatorial Countercurrent.

North Pacific Current An ocean current that flows from west to east across the North Pacific Ocean, carrying warm water toward California. It is an extension of the Kuroshio Current.

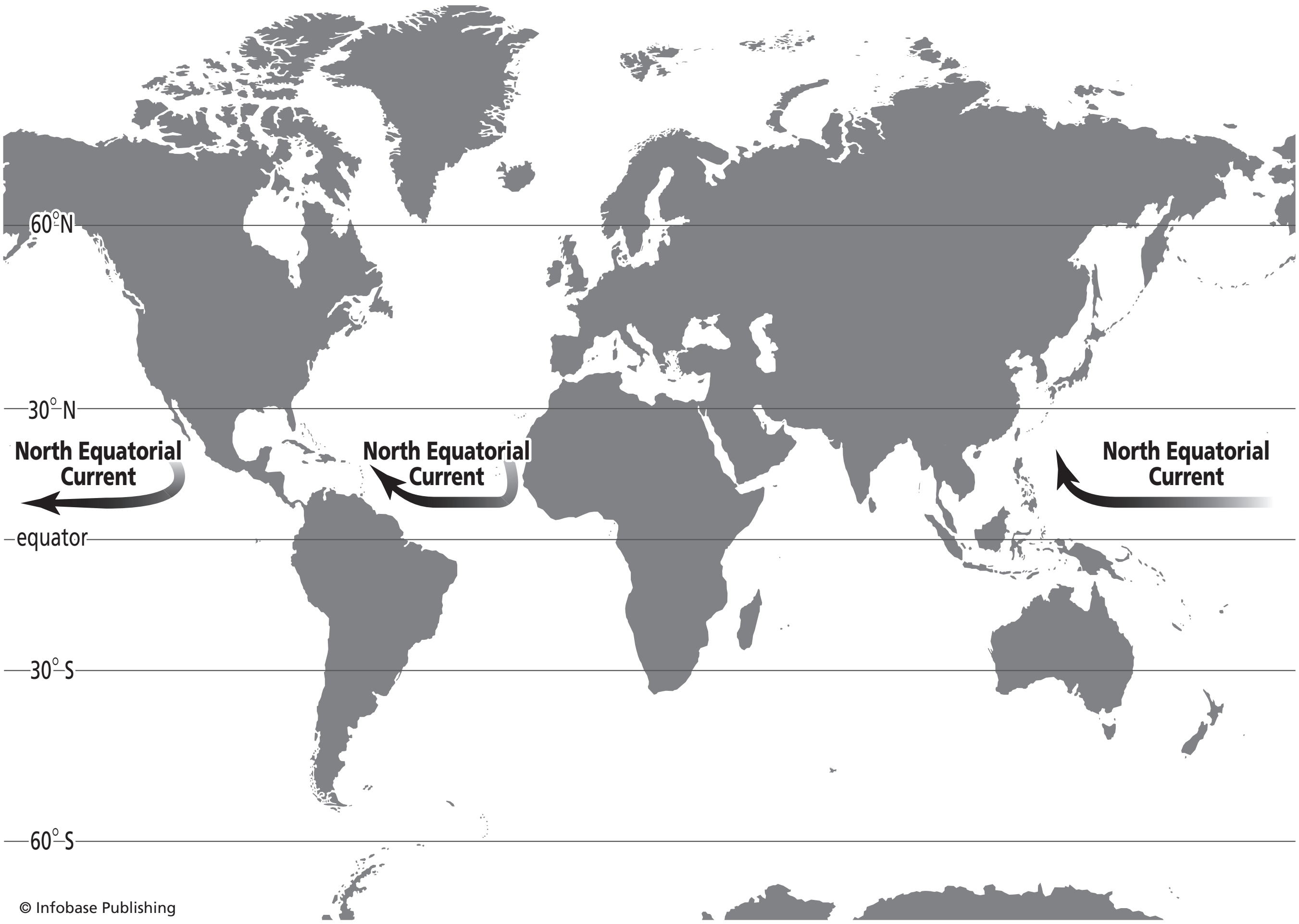
Norwegian Current (Norway Current) An ocean current that flows in a northeasterly direction, parallel to the northern coast of Norway. It is a continuation of the North Atlantic Drift and carries relatively warm water into the Arctic Ocean.

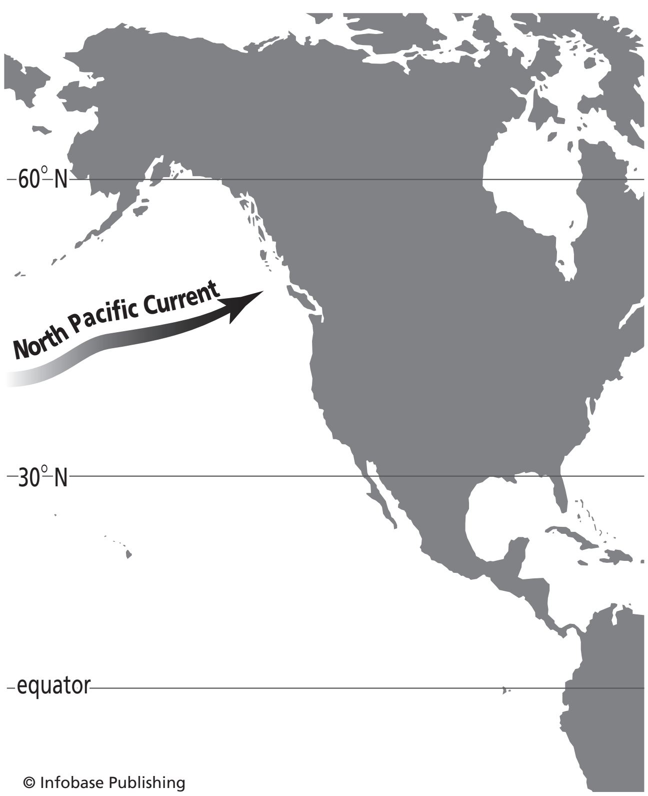
Oyashio Current (Kamchatka Current) An ocean current that flows southward from the Bering Sea, past the Kuril Islands, to the northeast of Japan, where it meets the Kuroshio Current. It flows at less than 1.5 MPH (2.4 km/h) and carries cold water, with a low salinity of 33.7–34.0 per mil.

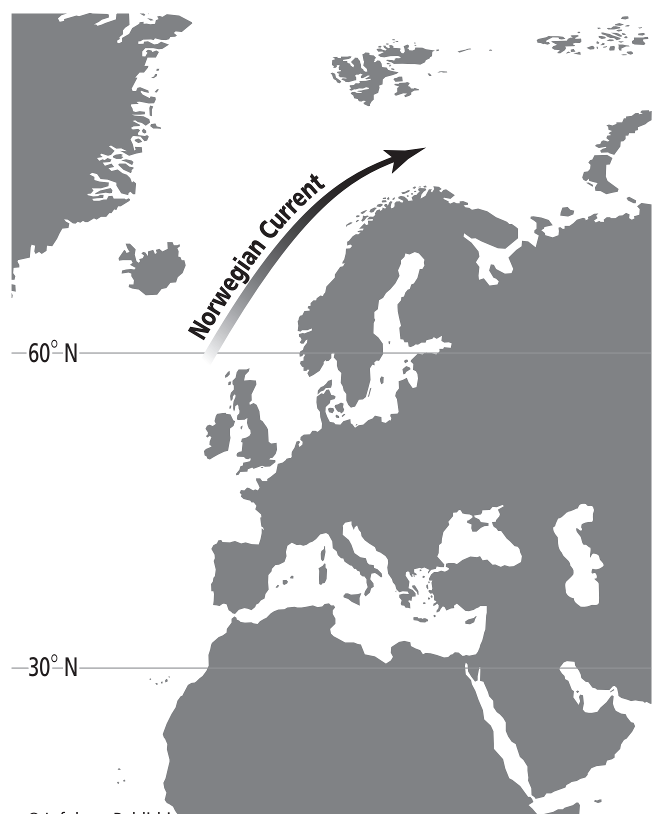
Peru Current (Humboldt Current) An ocean current that flows northward from the Antarctic Circumpolar Current, past the western coast of South America, to join the South Equatorial Current. It carries cold water and is broad and slow-moving. The current is noted for the many UPWELLINGS along its course, which bring nutrients near to the surface.

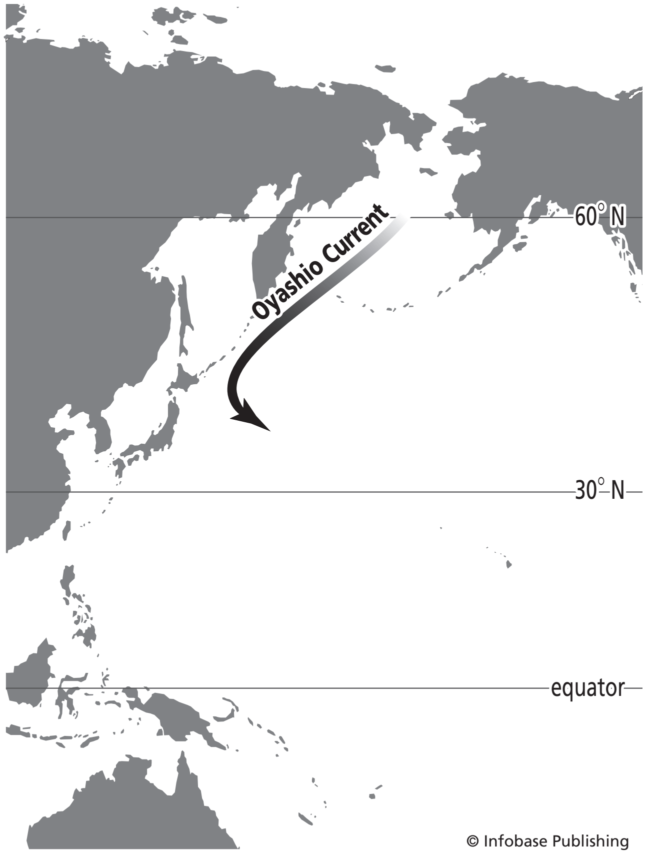
South Equatorial Current Two ocean currents, one in the South Atlantic and the other in the South Pacific, that flow from east to west parallel to and just south of the equator. The current flows within the upper 1,600 feet (500 m) of water at a speed of 0.6–2.5 MPH (1–4 km/h) and is separated from the North Equatorial Current by the Equatorial Countercurrent.

***(Opposite page: Top)* The North Equatorial Current flows just north of the equator and parallel to it, in the North Atlantic and North Pacific Oceans. Where it encounters continents, the current is deflected into a more northerly path.**
***(Bottom left)* The North Pacific Current carries warm water from Asia toward California.**
***(Bottom right)* The Norwegian Current is a warm current flowing parallel to the coast of Norway.**

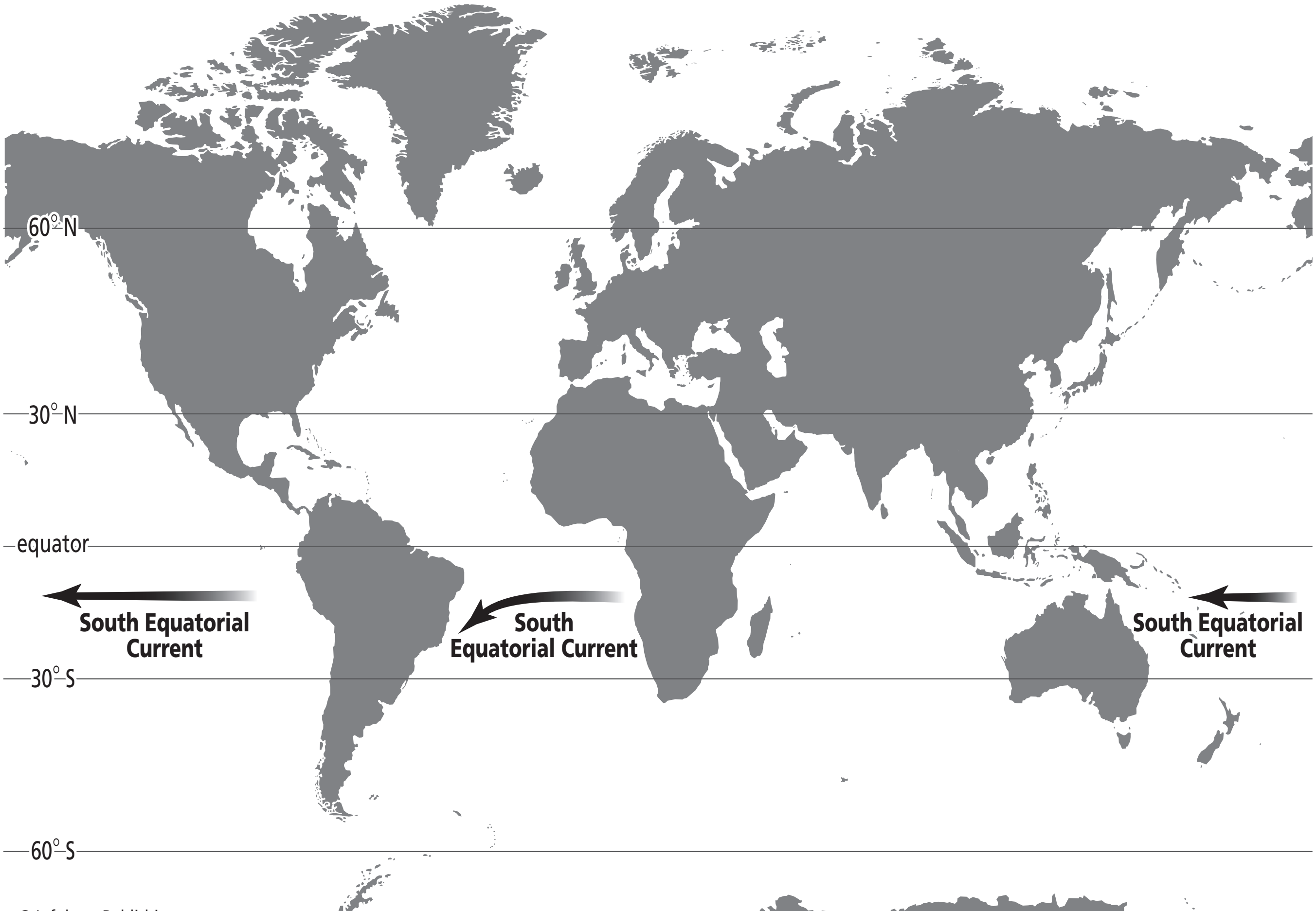

60° N
30° N
North Equatorial Current
North Equatorial Current
North Equatorial Current
equator
30° S
60° S
© Infobase Publishing


60° N
North Pacific Current
30° N
equator
© Infobase Publishing


Norwegian Current
60° N
30° N
© Infobase Publishing


60° N
Oyashio Current
30° N
equator

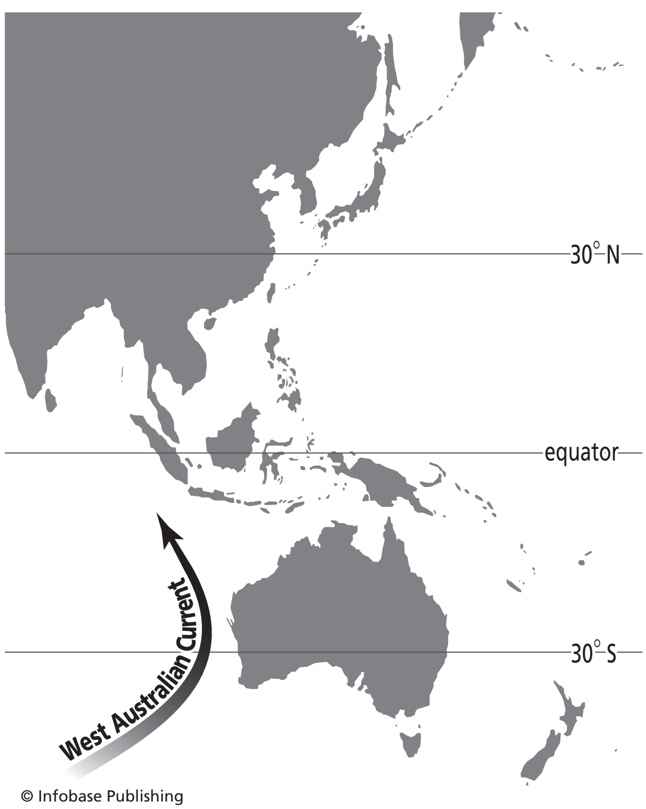

30° N
equator
Peru (Humboldt) Current
30° S


60° N
30° N
equator
South Equatorial Current
South Equatorial Current
South Equatorial Current
30° S
60° S

(Opposite page: Top left) **The Oyashio Current is a cold current flowing southward from Alaska toward Japan.**
(Top right) **The Peru (or Humboldt) Current is a cold current flowing northward from the Southern Ocean, parallel to the western coast of South America.**
(Bottom) **The South Equatorial Current flows from east to west close to the equator in the South Atlantic and South Pacific Oceans. Where it encounters continents, the current is deflected into a more southerly path.**

West Australian Current An ocean current that flows northward from the Antarctic Circumpolar Current, parallel to the western coast of Australia. The current flows strongly and steadily in summer, but weakens in winter. Its water is cold, at 37–45°F (3–7°C), and its salinity, of 34.5 per mil, is below the average for seawater.

West Greenland Current An ocean current that flows to the west of Greenland and that is an extension of the western branch of the North Atlantic Drift. It carries relatively warm water northward parallel to the western coast of Greenland and into the Davis Strait. The current then divides, part of it continuing into Baffin Bay and part joining the Labrador Current.



The West Australian Current is a cold current flowing from the Southern Ocean and passing close to the western coast of Australia.

The West Greenland Current is a warm current flowing parallel to the western coast of Greenland.

Appendix VII
Pliocene, Pleistocene, and Holocene Glacials and Interglacials

Approximate date ***('000 years BP)***	**N. America**	**Great Britain**	**N.W. Europe**
Holocene			
10–present	*Holocene*	*Holocene (Flandrian)*	*Holocene (Flandrian)*
Pleistocene			
75–10	Wisconsinian	Devensian	Weichselian
120–75	*Sangamonian*	*Ipswichian*	*Eeemian*
170–120	Illinoian	Wolstonian	Saalian
230–170	*Yarmouthian*	*Hoxnian*	*Holsteinian*
480–230	Kansan	Anglian	Elsterian
600–480	*Aftonian*	*Cromerian*	*Cromerian complex*
800–600	Nebraskan	Beestonian	*Bavel complex*
740–800	*Pastonian*		
900–800		Pre-Pastonian	Menapian
1,000–900		*Bramertonian*	*Waalian*
1,800–1,000		Baventian	Eburonian
Pliocene			
1,800		*Antian*	*Tiglian*
1,900		Thurnian	
2,000		*Ludhamian*	
2,300		Pre-Ludhamian	Pretiglian

BP means "before present" (present is taken to be 1950). Names in italic refer to interglacials. Other names refer to glacials (ice ages). Dates become increasingly uncertain for the older glacials and interglacials, and prior to about 2 million years ago evidence for these episodes has not been found in North America; in the case of the Thurnian glacial and Ludhamian interglacial, the only evidence is from a borehole at Ludham, in eastern England.

Appendix VIII
SI units and conversions

Unit	Quantity	Symbol	Conversion
Base units			
meter	length	m	1 m = 3.2808 feet
kilogram	mass	kg	1 kg = 2.205 pounds
second	time	s	
ampere	electric current	A	
kelvin	thermodynamic temperature	K	1 K = 1°C = 1.8°F
candela	luminous intensity		
mole	amount of substance	cd	mol
Supplementary units			
radian	plane angle	rad	$\pi/2$ rad = 90°
steradian	solid angle	sr	
Derived units			
coulomb	quantity of electricity	C	
cubic meter	volume yards^3	m^3	1 m^3 = 1.308
farad	capacitance	F	
henry	inductance	H	
hertz	frequency	Hz	
joule	energy	J	1 J = 0.2389 calories
kilogram per cubic meter	density	kg m^{-3}	1 kg m^{-3} = 0.0624 lb. $ft.^{-3}$
lumen	luminous flux	lm	
lux	illuminance	lx	
Unit	Quantity	Symbol	Conversion
meter per second	speed	m s^{-1}	1 m s^{-1} = 3.281 ft s^{-1}
meter per second squared	acceleration	m s^{-2}	
mole per cubic meter	concentration	mol m^{-3}	
newton	force	N	1 N = 7.218 lb. force
ohm	electric resistance	Ω	
pascal	pressure	Pa	1 Pa = 0.145 lb. in^{-2}
radian per second	angular velocity	rad s^{-1}	
radian per second squared	angular acceleration	rad s^{-2}	
square meter	area	m^2	1 m^2 = 1.196 yards^2
tesla	magnetic flux density	T	
volt	electromotive force	V	
watt	power	W	1W = 3.412 Btu h^{-1}
weber	magnetic flux	Wb	

Prefixes used with SI units

Prefix	Symbol	Value
atto	a	$\times 10^{-18}$
femto	f	$\times 10^{-15}$
pico	p	$\times 10^{-12}$
nano	n	$\times 10^{-9}$
micro	μ	$\times 10^{-6}$
milli	m	$\times 10^{-3}$
centi	c	$\times 10^{-2}$
deci	d	$\times 10^{-1}$
deca	da	$\times 10$
hecto	h	$\times 10^{2}$
kilo	k	$\times 10^{3}$
mega	M	$\times 10^{6}$
giga	G	$\times 10^{9}$
tera	T	$\times 10^{12}$

Prefixes attached to SI units alter their value.

Appendix IX
Chronology of Disasters

1246–1305
Drought in what is now the southwestern United States.

1281
A typhoon destroys a fleet of Korean ships carrying Mongol troops on their way to invade Japan. This is the kamikaze wind.

1703
On November 26 and 27, hurricane-force winds in the English Channel destroy 14,000 homes and kill 8,000 people in southern England.

1762
In February, a blizzard in England lasts for 18 days and kills nearly 50 people.

1831
A hurricane strikes Barbados, killing 1,477 people.

1865
In June, a tornado moves through Viroqua, Wisconsin, destroying 80 buildings and killing more than 20 people.

1875
On November 15, the River Thames rises, possibly by more than 28 feet (8.5 m), causing extensive flooding in London.

1876
A cyclone coinciding with high, monsoon, river levels floods islands in the Ganges Delta and on the mainland, drowning about 100,000 people in half an hour.

1879
On December 28, the Tay Bridge disaster causes 70–90 deaths in Scotland.

1887
In September and October, the Yellow River, China, floods about 10,000 square miles (26,000 km^2). Between 900,000 and 2.5 million people die.

1888
On March 11–13 blizzards with winds up to 70 MPH (113 km/h) strike the eastern United States. More than 400 people die, including 200 in New York City.

1925
In March, a series of possibly seven tornadoes develop over Missouri and cross Illinois and Indiana, killing 689 people.

1931
The Yangtze River, China, rises 97 feet (29.6 m) following heavy rain. About 3.7 million people die, some in the floods but most from the famine that follows.

1954
On October 12, Hurricane Hazel kills 1,175 people (1,000 of them in Haiti).

1956
On June 27, Hurricane Audrey kills near 400 people.

1957
In August, Hurricane Diane kills more than 190 people.

1959
In September, Typhoon Vera kills nearly 4,500 people and leaves 1.5 million homeless.

1966
On November 3, the River Arno floods Florence, Italy, causing extensive damage to historic buildings and works of art, killing 35 people, and leaving 5,000 homeless.

1969
On August 17–18, Hurricane Camille kills about 275 people.

1970
In November, a cyclone kills about 500,000 people in Bangladesh.

1973
On January 10, a TORNADO kills 60 people and injures more than 300 in San Justo, Argentina.

1974
On September 20, Hurricane Fifi kills about 5,000 people in Honduras. Cyclone Tracy strikes Darwin, Australia, on December 25.

1976
On September 8–13, Typhoon Fran kills 104 people and makes 325,000 homeless in Japan.

1977
On November 19, a cyclone and STORM SURGE washes away 21 villages and damages 44 more in Andhra Pradesh, India, killing an estimated 20,000 people and making more than 2 million homeless.

1978
On April 16, a TORNADO kills nearly 500 people and injured more than 1,000 in Orissa, India. On October 26, Typhoon Rita kills nearly 200 people and destroys 10,000 homes in the Philippines. On November 23, a cyclone kills at least 1,500 people and destroys more than 500,000 buildings in Sri Lanka and southern India.

1979
On April 10, a TORNADO kills 59 people and injures 800 at Wichita Falls, Texas. On May 12–13, a cyclone kills more than 350 people in India. On August 11, heavy rain causes a dam to break, flooding the town of Morvi, India, and killing up to 5,000 people. In August, Hurricane David kills more than 1,000 people in the Caribbean and eastern United States.

1980
In August, Hurricane Allen kills more than 270 people. A heatwave kills 1,265 people in the United States; in Texas, temperatures exceed 100°F (38°C) almost every day.

1981
On July 12–14, MONSOON rains cause the Yangtze River, China, to flood, killing about 1,300 people and leaving 1.5 million homeless. On September 1, typhoon Agnes kills 120 people in South Korea. On November 24, typhoon Irma kills more than 270 people and leaves 250,000 homeless in the Philippines.

1982
On January 23–24, floods kill at least 600 people and leave 2,000 missing in Peru. On June 3, MONSOON floods in Sumatra, Indonesia, kill at least 225 people and leave 3,000 homeless. In September, monsoon floods in Orissa, India, kill at least 1,000 people.

1983
In June, floods killed at least 935 people in Gujarat, India.

1984
Between January 31 and February 2, Cyclone DOMOINA kills at least 124 people. On September 2–3, Typhoon Ike kills more than 1,300 people in the Philippines. In November, typhoon Agnes kills at least 300 people in the Philippines and leaves 100,000 homeless.

1985
On May 25, a cyclone and STORM SURGE kill an estimated 2,540 people, but possibly as many as 11,000,

on islands off Bangladesh. On May 31, TORNADOES kill 88 people and cause extensive damage in Pennsylvania, Ohio, New York, and Ontario.

1986

On March 17, Cyclone Honorinnia kills 32 people and leaves 20,000 homeless in Madagascar. On September 4, a typhoon kills 400 people in Vietnam.

1987

In August, floods kill more than 1,000 people in Bangladesh. On November 26, typhoon Nina kills 500 people in the Philippines.

1988

In August and September, monsoon floods inundate 75 percent of Bangladesh, killing more than 2,000 people and leaving at least 30 million homeless. On September 12–17, Hurricane Gilbert kills at least 260 people in the Caribbean and Gulf of Mexico and generates nearly 40 TORNADOES in Texas. On October 24–25, Typhoon Ruby kills about 500 people in the Philippines. On November 7, Typhoon Skip kills at least 129 people in the Philippines. On November 29, a cyclone kills up to 3,000 people in Bangladesh and eastern India.

1989

On April 26, a TORNADO in Bangladesh kills up to 1,000 people and injures 12,000. On September 17–21, Hurricane Hugo kills more than 40 people in the Caribbean and eastern United States. On November 4–5, typhoon Gay kills 365 people in Thailand.

1990

On May 9, a cyclone kills at least 962 people in Andhra Pradesh, India. In August, typhoon Yancy kills 228 people in the Philippines and China. On August 28, a TORNADO kills 29 people and injures 300 at Plainfield, Illinois.

1991

On March 10, floods kill more than 500 people and leave 150,000 homeless in Mulanje, Malawi. On April 26, more than 70 TORNADOES kill 26 people and injure more than 200 in Kansas. On April 30, a cyclone kills at least 131,000 people on coastal islands off Bangladesh. On May 7, a tornado kills 100 people at Tungi, Bangladesh. In June, FLASH FLOODS kills up to 5,000 people in Jowzjan Province, Afghanistan.

1992

In July, floods kills more than 1,000 people in Fujian and Zheijiang Provinces, China. On August 23–26, Hurricane Andrew kills 38 people and causes extensive damage in the Bahamas, Florida, and Louisiana. On September 11–16, MONSOON rains cause the Indus River to flood, killing at least 500 people in India and more than 2,000 in Pakistan.

1993

On January 8, a TORNADO kills 32 people and injures more than 1,000 in Bangladesh. On March 12–15, a BLIZZARD kills at least 238 people in the eastern United States, four in Canada, and three in Cuba. Between October 31 and November 2, mudslides kill 400 people and destroy 1,000 homes in Honduras.

1994

On February 2–4, Cyclone Geralda kills 70 people and leaves 500,000 homeless in Madagascar. On August 20–21, Typhoon Ted kills about 1,000 people in Zheijiang Province, China. On November 13–19, Tropical Storm Gordon kills 537 people in the Caribbean, Florida, and South Carolina.

1995

Beginning in July, floods affect 5 million people, nearly 25 percent of the population, in North Korea. On November 3, Typhoon Angela kills more than 700 people and leaves more than 200,000 homeless in the Philippines.

1996

On May 13, a TORNADO in Bangladesh destroys 80 villages in less than half an hour, killing more than 440 people and injuring more than 32,000. On September 10, Typhoon Sally kills more than 130 people and destroy nearly 400,000 homes in Guangdong, China.

1996–1997

In December and January, floods in California, Idaho, Nevada, Oregon, and Washington cause at least 29 deaths and force 125,000 people to leave their homes.

1997

In January, a COLD WAVE crosses Europe kills at least 228 people. On May 2, a SANDSTORM kills 12 people and injures 50 in Egypt. On May 27, TORNADOES in central Texas destroy about 60 homes and kill 30 people. On July 2, THUNDERSTORMS and tornadoes in southern Michigan destroy 339 homes and business premises, kill 16 people, and injure more than 100. On August 18–19, Typhoon Winnie kills nearly 200 people in China, Taiwan, and the Philippines. On October 8–10, Hurricane Pauline kills 217 people and leaves 20,000 homeless in southern Mexico. On October 12, a tornado kills at least 25 people and injures thousands who had gathered for a religious ceremony at Tongi, Bangladesh. In November, Typhoon Linda kills at least 484 people in Vietnam, Cambodia, and Thailand.

1998

On February 23, TORNADOES in Florida kill at least 42 people, injure more than 260, and leave hundreds homeless. On March 20, tornadoes kill at least 14 people and injure 80 in Georgia and kill two and injure at least 22 in North Carolina. In March, a cyclone kills at least 200 people and makes 10,000 homeless in West Bengal and Orissa, India. On April 8–9, tornadoes kill 39 people in Mississippi, Alabama, and Georgia. In May and early June, a heat wave kills at least 2,500 people in India. From June to August, the Yangtze River, China, floods, killing 3,656 people and affecting an estimated 230 million. On September 21–28, Hurricane Georges kills more than 330 people in the Caribbean and along the U.S. Gulf coast. In September and early October Tropical Storm Yanni kills 27 people in South Korea. In October, typhoon Zeb kills 111 people in the Philippines, Taiwan, and Japan. In late October, Hurricane Mitch kills more than 8,600 people, leaving 12,000 unaccounted for, and makes more than 1.5 million homeless in Central America. In late October, Typhoon Babs kills at least 132 people and makes about 320,000 homeless in the Philippines. On November 19–23 typhoon Dawn causes floods in Vietnam that force 200,000 people from their homes and kill more than 100.

1999

In August, typhoon Olga causes extensive flooding in South Korea. In September, Hurricane Floyd kills 49 people in the Bahamas and the eastern coast of the United States.

2000

In February, the worst floods in 50 years devastate Mozambique, destroying about 200,000 homes. Shortly after midnight on February 14, TORNADOES sweeping through southwestern Georgia kill 18 people and injure about 100. On February 22, Cyclone Eline strikes Mozambique, with winds of up to 162 MPH (260 km/h). Eline moves to Madagascar, which is also struck by Tropical Storm Gloria on March 4–5. The two storms leave at least 500,000 people homeless on the island and kills at least 137. In May, severe flooding combine with a tidal surge, killing at least 140 people and leaving about 20,000 homeless on West Timor, Indonesia. Between late July and early October, the Mekong Delta, in Vietnam, Laos, and Cambodia, experiences the worst flooding in 40 years, killing at least 315 people. In September and October, flooding kills more than 900 people in India and about 150 in Bangladesh, and leaves some 5 million homeless in the two countries. On November 1–2, typhoon Xangsane causes severe flooding on Taiwan.

2001

Floods early in the year kill at least 52 people in Mozambique and leave more than 80,000 homeless. In January, a BLIZZARD in northern China kills 20 people and leaves thousands cut off, with no access to food supplies. In February, TORNADOES kill five people in Mississippi and one in Arkansas. In April, the Mississippi bursts its banks, flooding parts of Minnesota, Iowa, Illinois, and Wisconsin. A 165-foot (50-m) dam of ice blocks cause the River Lena, in Siberia, to flood in May, washing away thousands of homes and killing at least five people. On May 28, 18 people are injured and many buildings damaged by a tornado in Ellicott, Colorado. Weekend storms on July 7–8 cause widespread flooding in West Virginia. In July, Typhoon Utor causes floods and a mudslide in which 23 people die in the Philippines and one person dies in Taiwan. Two days of rain in South Korea, also in July, cause 40 deaths. On July 29 and 30, Typhoon Toraji swept through Taiwan, causing at least 72 deaths and leaves more than 130 unaccounted for. MONSOON floods in late July trap nearly 50,000 people in inundated villages in Bangladesh.

2002

Heavy rain and extreme cold in Mauritania in January kill at least 25 people and an estimated 80,000 head of livestock. Winds of almost 120 MPH (200 km/h) batter Europe in late January, killing at least 18 people. Heavy rain causes floods and landslides in Java, Indonesia, in February. At least 150 people die. On February 19, the most destructive storm ever experienced in La Paz, Bolivia, triggers FLASH FLOODS and mudslides that kill 69 people and leave hundreds homeless. From May 9 to 15, an intense heat wave in Andhra Pradesh, India, kills at least 1,030 people. In early June, a heat wave kills more than 60 people in Nigeria. In June, floods kill more than 200 people in northwestern China. Floods in June inundate approximately 70 villages in southern Russia, killing at least 53 people and rendering 75,000 homeless. MONSOON floods lasting from June until the middle of August in southern Asia kill at least 422 people in Nepal, nearly 400 in India, and at least 157 in Bangladesh. Approximately 15 million people are made homeless in Bihar and Assam States, India, and about 6 million in Bangladesh. On June 4–5, the Zeyzoun Dam near the town of Hama, Syria, collapses following prolonged heavy rain. Several villages were flooded and at least 28 people are killed. In July, a heat wave in Algeria produces temperatures up to 133°F (56°C) and kill at least 50 people. Severe cold weather in July kills at least 59 people in Peru, and about 80,000 head of livestock die. Heavy rain causes flooding and triggers landslides in southern China in August. At least 133 people die. In mid-August, prolonged rain causes extensive flooding in central Europe and southern Russia. At least 100 people die. At least 113 people are killed in South Korea on August 31 and September 1, when Typhoon Rusa brings winds of more than 125 MPH (200 km/h) and widespread flooding. In September, floods cause heavy rain, killing 23 persons around Sommières, France. On October 26–27, a storm crosses northern Europe, killing seven people in Britain, six in France, at least 10 in Germany, five in Belgium, four in the Netherlands, and one in Denmark. From November 9 to 11, a storm front sweeps through the southeastern and midwestern United States, generating almost 90 TORNADOES and killing 36 people. An ICE STORM strikes North and South Carolina on December 4–5, disrupts power supplies to 1.8 million people, and is probably responsible for at least 22 deaths. On December 8–9, heavy rain triggers mudslides that bury many homes in Angra dos Reis, Brazil, and kill at least 34 people. During late December, extremely cold weather claims at least 100 lives in northern Bangladesh.

2003

On January 16, mudslides due to heavy rain kill at least 14 people in Minas Gerais State, Brazil. Widespread flooding in northern Mozambique in February destroys about 6,000 homes and kills at least 47 people. In mid-February, a huge snowstorm dumps about two feet (60 cm) of snow along the eastern seaboard of the United States, killing 59 people. On February 17, storms bringing heavy rain and snow in southern Pakistan, Kashmir, and Afghanistan cause floods and destroy houses and a bridge, killing a total of 86 people. On March 31, a mudslide triggered by heavy rain engulfs the gold-mining town of Chima, Bolivia, killing at least 14 people. FLASH FLOODS and mudslides wash away homes and kill at least 29 people in Flores Island, Indonesia, on April 1. On April 20, a mudslide destroys the town of Kurbu-Tash, Kyrgyzstan. At least 38 people die, and the area is declared a grave because it proves impossible to recover the bodies. THUNDERSTORMS kill at least 33 people in Assam State, India, on April 22. Heavy rain in May cause floods in the Horn of Africa in which more than 160 people die. A TORNADO outbreak, with more than 300 tornadoes, sweeps through several southern and midwestern states of the United States from May 4 to May 12. The tornadoes destroy entire towns and kill at least 42 people. On May 4, a tropical storm causes a landslide that engulfs a village in Bangladesh, killing at least 23 people. A heat wave and drought lasting from mid-May until June 10 causes a shortage of drinking water that results in the deaths of 1,522 people in India, 40 in Pakistan, and more than 60 in Bangladesh. On May 16, mudslides and FLASH FLOODS wash away factories and bury the homes of coal miners in Wanshui, Hunan Province, China, killing at least 12 people. On May 17, more than 300 people die in Sri Lanka during floods and landslides caused by heavy rain. Tropical Storm Linfa kills at least 25 people in Luzon, Philippines, on May 27. At least 32 people lose their lives when they are either swept away or buried by floods and mudslides in Bangladesh on June 26. The MONSOON rains deliver 4.5 inches (120 mm) in 24 hours. On July 7, monsoon rains swell the Jamuna River, which breaks its banks and sweeps away several villages. An intense heat wave and drought lasting from mid-July until mid-August in western Europe causes the deaths of approximately 14,800 people in France, 4,200 in Italy, 1,400 in the Netherlands, 1,300 in Portugal, 900 in Britain, and 100 in Spain. More than 100 people die in Himachal Pradesh State, India, on July 16 when a cloudburst causes FLASH FLOODS that sweep away a camp housing migrant workers at a hydroelectric project. At least 88 people die in late July in Sind, Pakistan, and 100,000 lose their homes due to floods caused by monsoon rains. Floods in Kassala Province, Sudan, kill 20 people and make 250,000 homeless in early August. Floods in Haiti leave 20 people dead in early September. Typhoon Maemi kills at least 124 people in South Korea on September 12. About 40 people die in the eastern United States when Hurricane Isabel strikes on September 18. On November 2, flash floods destroy a tourist village in Sumatra, Indonesia, killing about 200 people. In mid-November, floods kill at least 50 people in Vietnam. A rare winter cyclone on December 16 destroys the homes and crops of about 8,000 people in Andhra Pradesh State, India, and kills at least 50. At least 200 people die on December 19 in Leyte Province, Philippines, when mudslides engulf entire villages and towns. Extreme cold weather late in December kills more than 200 people in northern India.

2004

On March 7, Cyclone Gafilo kills about 200 people in Madagascar and leaves hundreds of thousands homeless. FLASH FLOODS kill at least 34 people in Piedras Negras, Mexico, on April 5. On April 14, TORNADOES destroy thousands of homes in northern Bangladesh and kill at least 66 people. Floods in April kill at least 16 people in Kenya and 30 in Djibouti. On April 23, a mudslide engulf a bus in Sumatra, Indonesia, killing at least 37 people. A heat wave in May kills at least 17 people in Bangladesh. On May 19, typhoon Nida destroys several villages and kills 19 people in Catanduanes Province, Philippines. Nida was classed as a supertyphoon (*see* TROPICAL CYCLONE). On May 24, heavy rain cause floods and mudslides that kill almost 2,000 people in Haiti and the Dominican Republic. Extreme MONSOON rain and storms across southern Asia kills almost 2,000 people between June and August. Typhoon Mindulle kills 31 people in Luzon, Philippines, on June 29 and 15 in Taiwan on July 1. Floods and landslides kill nearly 400 people in southern and central China in early July. Taiwan suffers its worst floods for 25 years in early July; at least 21 people die. Typhoon Rananim kills at least 164 people in Zhejiang province, China, on August 12. On August 12, FLASH FLOODS in Adamawa state, Nigeria, drown at least 23 people while they sleep. Hurricane Charley strikes Florida on August 13, killing at least 27 people. Typhoon Aere kills at least 24 people in Taiwan and five people in the Philippines on August 24. Hurricane Ivan crosses the Caribbean and the U.S. Gulf coast from September 7 to September 17, destroying crops in Grenada and killing at least 109 people, including 52 in the United States. At the end of the three-month rainy season in early September, floods kill more than 1,000 people in China. On September 18, tropical storm Jeanne strikes Haiti, causing floods in which more than 3,000 people die. Flash floods kill at least 44 people on September 21 in Uttar Pradesh State, India. On October 9, flash floods kill more than 100 people in Assam State, India, and at least 44 in Bangladesh. Typhoon Tokage kills at least 83 people in Japan on October 20. On November 29, Typhoon Winnie causes floods and landslides in the Philippines in which at least 412 people die. On December 2, while rescuers are still searching for survivors from Typhoon Winnie, Typhoon Nanmadol strikes the Philippines, leaving more than 1,000 people dead or missing. On December 26, a Richter magnitude 9.0 earthquake beneath the seabed off the coast of Sumatra, Indonesia, causes TSUNAMIS that kill more than 250,000 people in Sumatra's Aceh Province, Sri Lanka, India, the Maldives, and Thailand.

2005

On January 8–9, storms across northern Europe kill at least 11 people. Prolonged heavy rain and snow in Southern California kill approximately 20 people in early January, and on January 10 a hillside collapses at La Conchita, burying four blocks and killing at least 10 people. A storm on January 22, the last day of the Hajj, causes FLASH FLOODS that kill approximately 29 people in Medina, Saudi Arabia. In late January, Georgetown, Guyana, suffers its worst flooding for a century. Thousands of people are forced to evacuate their homes, and 34 die, mainly from diseases. In early February, flooding kills at least 53 people in Venezuela and 33 in Colombia. Heavy rainfall causes the failure of the Shadi Khor Dam, in Balochistan Province, Pakistan, on February 10; at least 60 people die. Heavy rain and snow cause the deaths of 65 people in North-West Frontier Province, Pakistan, in early February. At least 278 die on February 20 when AVALANCHES destroy several villages in Indian-administered Kashmir. Approximately 120 people are dead or missing in Java, Indonesia, when on February 21 heavy rains cause a municipal waste dump sited on the top of a hill to collapse, triggering a landslide that partly buries the village of Cimahi. A TORNADO kills 56 people and leaves thousands homeless on March 20 in the Gaibandha district of northern Bangladesh. At least 123 people die on April 23 in the Somali region of Ethiopia when the Shebeli River overflows its banks, flooding the surrounding area. Storms and flash floods kill approximately 30 people in Jiddah, Saudi Arabia, on April 28. On May 18, a BLIZZARD kills at least 26 soldiers on a training march in the Andes Mountains, Chile. At least 92 people drown at Shalan, in Heilongjiang Province, China, on June 10, when about eight inches (200 mm) of rain fall in 40 minutes, causing flash floods. A mudslide buries homes killing at least 23 people in Senahú, Guatemala, on June 16. Flooding in China kills 536 people between June 10 and June 24. MONSOON floods kill at least 94 people in Gujarat, India, in late June. Hurricane Dennis strikes Haiti on July 7, killing at least 60 people, and on July 8 it kills 16 people in Cuba. Heavy rain in early July destroys 26,000 homes in southern China and kills at least 29 people. On July 26, 37.1 inches (942 mm) of rain fall on Mumbai, India, in 24 hours, paralyzing the city and causing at least 736 deaths. Category 4 hurricane Katrina strikes the U.S. Gulf coast on August 29, causing devastation in New Orleans and Slidell, Louisiana, and Gulfport and Biloxi, Mississippi. On August 30, the New Orleans levees are breached in three places, flooding about 80 percent of the city. A total of 972 lives are lost in Louisiana and 221 in Mississippi. Rain trigger a landslide on September 1 in Sumatera Province, Indonesia, killing at least 10 people and leaving 34 buried in rubble. Landslides and flooding caused by Typhoon Talim kill 53 people in Anhui Province, China, on September 1. Typhoon Nabi strikes southern Japan on September 6, forcing 250,000 people to evacuate their homes and killing at least 18. Typhoon Khanun strikes Zhejiang Province, China, on September 11, killing at least 14 people and destroying more than 7,000 homes. Between about September 20 and 28, when it is downgraded to a tropical storm, Typhoon Damrey kills 36 people in Vietnam, 16 in the Philippines, 16 in southern China, and at least three in Thailand. At least 80 students are killed on October 2 at a military school in Fuzhou, Fujian Province, China, by floodwaters released by Typhoon Longwang. Hurricane Stan strikes Central America on October 4, triggering landslides and floods that kill at least 71 people in El Salvador, 654 in Guatemala, and 60 in Nicaragua, Honduras, Mexico, and Costa Rica. Hurricane Wilma strikes Mexico on October 21, devastating the resorts of Cancún, Cozumel, and Playa del Carmen and killing six people. Wilma makes landfall on the U.S. coast on October 24, killing approximately 22 people. On October 23, tropical storm Alpha becomes the 22nd named storm in the 2005 season, making this the most active hurricane season ever recorded in the Atlantic and Caribbean region. Alpha causes floods that kill at least 26 people in Haiti and the Dominican Republic. More than 100 people are reported dead in southern India on October 27 following five days of heavy rain. A TORNADO kills 24 people in Indiana on November 6. An AVALANCHE kills 24 gemstone miners in Pakistan on December 28.

2006

On January 2, heavy snow causes the roof of an ice-skating rink at Bad Reichenhall, Germany, to collapse, killing 15 people. Heavy snowstorms dump two feet (60 cm) or more of snow across the northeastern United States on February 11–12, closing airports in Washington, D.C., and New York and bringing road traffic almost to a standstill; 26.9 inches (68 cm) of snow fall in New York City. On February 17, a mudslide caused by the collapse of a mountainside engulfs the town of Guinsaugon, Philippines, burying more than 1,000 people, few of whom survive. Between March 9 and March 13, at least 105 TORNADOES affect five southern and midwestern U.S. states, killing at least 11 people. In early April, melting snow and heavy rain cause rivers to overflow, producing widespread flooding in central Europe. The Danube overflows its banks and breaches flood defenses. Several thousand people have to leave their homes in Serbia, Romania, and Bulgaria. Flooding finally reaches the Danube delta, in Ukraine. On April 2, at least 28 people die in storms that cross Arkansas, Indiana, Illinois, Iowa, Kentucky, Ohio, Mississippi, and Tennessee, triggering at least 63 tornadoes. On April 13, a landslide caused by heavy rain kills 31 people near Buenaventura, Colombia. On May 11–13, Typhoon Chanchu crosses the Philippines; 41 people are killed and thousands are made homeless. Chanchu makes landfall in China on May 17, causing at least 29 deaths; 28 Vietnamese fisherman also die, and 150 are reported missing. On June 19, heavy rain triggers a landslide in Shiji village, Fujian Province, China, killing 11 people. On June 19–20 torrential rain causes flooding in eastern Sulawesi, Indonesia; at least 216 people die. On June 25, a FLASH FLOOD kills 11 people in Hunan Province, China. Between July 16 and 25 a heat wave across the United States, affecting California most severely, brings temperatures in excess of 104°F (40°C); 140 persons die.

Appendix X
Chronology of Discoveries

ca. 340 B.C.E.
Aristotle (*see* Appendix I: Biographical Entries) writes *Meteorologica,* the oldest known work on meteorology and possibly the first. It gives us the word *meteorology.*

140–131 B.C.E.
Han Ying, in China, writes *Moral Discourses Illustrating the Han Text of the* Book of Songs. This contains the first known description of the hexagonal structure of snowflakes.

first century B.C.E.
The Tower of the Winds is built in Athens. It is possibly the first attempt to forecast the weather systematically on the basis of observations.

ca. 55 B.C.E.
Lucretius Carus (ca. 94–55 B.C.E.) proposes that thunder is the sound of great clouds crashing together. Although he is wrong, he may have been the first person to notice that thunder is always associated with big, solid-looking clouds.

first century C.E.
Hero of Alexandria (*see* Appendix I: Biographical Entries) demonstrates that air is a substance.

1555
Olaus Magnus (*see* Appendix I: Biographical Entries) publishes a book containing the first European depictions of ice crystals and snowflakes.

1586
Simon Stevinus (*see* Appendix I: Biographical Entries) shows that the pressure a liquid exerts on a surface depends on the height of the liquid above the surface and the area of the surface on which it presses, but it does not depend on the shape of the vessel containing the liquid.

1593
Galileo (*see* Appendix I: Biographical Entries) invents an air thermoscope (*see* thermometer).

1611
Johannes Kepler (*see* Appendix I: Biographical Entries) publishes *A New Year's Gift, or On the Six-cornered Snowflake* in which he described snowflakes.

1641
Ferdinand II (*see* Appendix I: Biographical Entries) invents a thermometer consisting of a sealed tube containing liquid.

1643
Evangelista Torricelli (*see* Appendix I: Biographical Entries) invents the barometer.

1646
Blaise Pascal (*see* Appendix I: Biographical Entries) demonstrates that atmospheric pressure decreases with height.

1654
Ferdinand II (*see* Appendix I: Biographical Entries) improves on his thermometer, producing the design

that will lead to the mercury thermometer invented by Daniel Fahrenheit in 1714.

1660

Robert Boyle (*see* Appendix I: Biographical Entries) publishes his discovery of the relationship between the volume occupied by a gas and the pressure under which the gas is held.

1686

Edmund Halley (*see* Appendix I: Biographical Entries) proposes the first explanation for the trade winds (*see* wind systems).

1687

Guillaume Amontons (*see* Appendix I: Biographical Entries) invents the hygrometer.

1714

Daniel Fahrenheit (*see* Appendix I: Biographical Entries) invents the mercury thermometer and the temperature scale that bears his name.

1735

George Hadley (*see* Appendix I: Biographical Entries) proposes his model of the circulation of the atmosphere to explain the direction from which the trade winds blow (*see* general circulation).

1738

Daniel Bernoulli (*see* Appendix I: Biographical Entries) demonstrates that when the velocity of a flowing fluid increases, its internal pressure decreases.

1742

Anders Celsius (*see* Appendix I: Biographical Entries) proposes the temperature scale that bears his name.

1752

Benjamin Franklin (*see* Appendix I: Biographical Entries) performs his experiment with a kite, demonstrating that storm clouds carry electric charge and that a lightning stroke is a giant spark.

1761

Joseph Black (*see* Appendix I: Biographical Entries) demonstrates that when ice melts it absorbs heat with no rise in its own temperature. He later shows that heat is absorbed or released when water vaporizes and condenses. He calls this latent heat.

1783

Horace Bénédict de Saussure (*see* Appendix I: Biographical Entries) invents the hair hygrometer.

1806

Admiral Sir Francis Beaufort (*see* Appendix I: Biographical Entries) proposes a scale for classifying wind forces.

1820

John Daniell (*see* Appendix I: Biographical Entries) invents the dewpoint hygrometer.

1824

John Daniell shows the importance of maintaining a humid atmosphere in hothouses growing tropical plants.

1827

Jean-Baptiste Fourier (*see* Appendix I: Biographical Entries) writes what is possibly the first account of the greenhouse effect.

1835

Gaspard de Coriolis (*see* Appendix I: Biographical Entries) explains why anything moving over the surface of the Earth, but not attached to it, is deflected by inertia acting at right angles to its direction of motion.

1840

Louis Agassiz (*see* Appendix I: Biographical Entries) discovers that glaciers move and that they had once covered a much larger area than they do now.

1842

Matthew Maury (*see* Appendix I: Biographical Entries) discovers the shape of storms from data gathered from ships at sea.

Johann Christian Doppler (*see* Appendix I: Biographical Entries) discovers the effect bearing his name, that the pitch of a sound rises and light becomes bluer if the source is approaching, and the pitch of a sound falls and light becomes redder if the source is receding.

1844
The world's first telegraph line opens between Baltimore and Washington.

1846
Joseph Henry (*see* Appendix I: Biographical Entries) is elected secretary of the Smithsonian Institution and uses his position to obtain weather reports from all over the United States.

1851
The first weather map is exhibited at the Great Exhibition in London, England.

1855
Urbain-Jean-Joseph Leverrier (1811–77; *see* Appendix I: Biographical Entries) begins supervising the installation of a network to gather meteorological data from observatories across Europe.

1856
William Ferrel (*see* Appendix I: Biographical Entries) finds that winds blowing close to the equator are deflected by vorticity, not the Coriolis effect, and that once established they continue to rotate in order to conserve angular momentum. He also proposes that in the Northern Hemisphere winds blow counterclockwise around areas of low pressure.

1857
C. D. H. Buys Ballot (*see* Appendix I: Biographical Entries) proposes the law bearing his name (but discovered earlier by William Ferrel).

1858
The first weather bulletins are issued in France on January 1, containing observations from 14 French cities and four cities outside France.

1861
The Meteorological Department of the Board of Trade issues the first British storm warnings for coastal areas on February 6 and for shipping on July 31.

John Tyndall (*see* Appendix I: Biographical Entries) shows that certain atmospheric gases absorb heat, and therefore, that the chemical composition of the atmosphere affects climate.

1863
The first network of meteorological stations to be linked to a central point by telegraph open in France. From September the *Bulletin International de l'Observatoire de Paris* includes a daily weather map.

Francis Galton (*see* Appendix I: Biographical Entries) devises a method for mapping weather systems and coined the term *anticyclone*.

1869
The first daily weather bulletins begin to be issued from Cincinnati Observatory on September 1.

1871
The first three-day weather forecasts are issued by the Weather Bureau.

1874
The International Meteorological Congress is founded.

1875
A weather map appears in a newspaper, *The Times* of London, for the first time.

1884
S. P. Langley (*see* Appendix I: Biographical Entries) publishes a paper on the climatic effect of the absorption of heat by atmospheric gases.

1891
The U.S. Weather Bureau is founded.

1893
Edward Maunder (*see* Appendix I: Biographical Entries) discovers the link between solar activity and the Little Ice Age.

1896
Svante Arrhenius (*see* Appendix I: Biographical Entries) links climatic changes to the atmospheric concentration of carbon dioxide.

The International Meteorological Congress publishes the first edition of the *International Cloud Atlas*.

1902

L. P. Teisserenc de Bort (*see* Appendix I: Biographical Entries) discovers the stratosphere (*see* atmospheric structure).

Vilhelm Bjerknes (*see* Appendix I: Biographical Entries) publishes one of the first scientific studies of weather forecasting.

1905

V. W. Ekman (*see* Appendix I: Biographical Entries) discovers that the deflection of winds and ocean currents changes with vertical distance from the surface.

1913

Charles Fabry (*see* Appendix I: Biographical Entries) discovers the ozone layer.

1918

W. P. Köppen (*see* Appendix I: Biographical Entries) publishes a system for classifying climates.

1918

Vilhelm Bjerknes establishes the existence of air masses.

1922

L. F. Richardson (*see* Appendix I: Biographical Entries) describes a method for numerical weather forecasting.

1923

Gilbert Walker describes the high-level flow of air from west to east close to the equator. He also describes the southern oscillation that is linked to El Niño events (*see* enso).

1930

Milutin Milankovitch (*see* Appendix I: Biographical Entries) proposes a link between the onset and ending of glacial periods and variations in the Earth's orbit and rotation.

1931

Wilson Bentley (*see* Appendix I: Biographical Entries) publishes more than 2,000 photographs of snowflakes.

C. W. Thornthwaite (*see* Appendix I: Biographical Entries) publishes a system for classifying climates.

1940

Carl-Gustav Rossby (*see* Appendix I: Biographical Entries) discovers large-wavelength undulations in the westerly winds of the upper atmosphere.

1946

Vincent Schaeffer (*see* Appendix I: Biographical Entries) discovers that pellets of dry ice (solid carbon dioxide) can trigger the formation of ice crystals.

1949

Radar is used for the first time to obtain meteorological data.

1951

An international system for the classification of snowflakes is adopted.

1959

The U.S. Weather Bureau begins publishing a temperature-humidity index as an indication of how comfortable the air will feel on a warm day.

1960

The first weather satellite, *Tiros 1,* is launched.

1964

The *Nimbus 1* weather satellite is launched.

1966

The first satellite to be placed in a geostationary orbit is launched on December 6.

1971

The Fujita Tornado Intensity Scale is published.

1973

Doppler radar is used successfully for the first time to study a tornado.

1974

The first of the GOES (Geostationary Operational Environmental Satellite) is launched.

F. Sherwood Rowland and Mario Molina (*see* Appendix I: Biographical Entries for information about Rowland and Molina) propose that CFCs might deplete stratospheric OZONE.

1977

Meteosat-1, the first European meteorological satellite, is launched on November 23. It remains operational until 1985.

1979

Edward Lorenz (*see* Appendix I: Biographical Entries) presents a paper describing what came to be called the BUTTERFLY EFFECT.

1981

Meteosat-2 is launched in June.

1985

Depletion of the ozone layer over Antarctica is discovered by J. C. Farman, B. G. Gardiner, and J. D. Shanklin of the British Antarctic Survey.

1988

The Intergovernmental Panel on Climate Change (IPCC) is founded.

1989

Meteosat-4 is launched.

1990

The IPCC publishes its first report in June, summarizing scientific understanding of climate change at that time.

1992

The Topex/Poseidon satellite is launched, with instruments to measure sea level.

The IPCC publishes its second report in February.

1993

Using powerful computers and advanced climate models, the National Weather Service is able to predict a major storm five days in advance.

1995

F. Sherwood Rowland, Mario Molina, and Paul Crutzen (*see* Appendix I: Biographical Entries) share the Nobel Prize in chemistry for their work on the ozone layer.

1996

Technological advances mean five-day forecasts are as accurate as three-day forecasts were in 1980.

1999

The Drought Monitor program is launched to provide weekly updates on drought conditions in the United States.

2001

The IPCC publishes its third report.

2002

Preparations are made to expand the Drought Monitor program to cover Canada and Mexico as well as the United States; the new service will be called the North American Drought Monitor.

2007

The Intergovernmental Panel on Climate Change (IPCC) publishes its fourth report.

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