piston cores by the French research vessel *Marion Dufresne*, which in its present international phase of drilling (IMAGES) provides most material for studies covering the last few hundred thousands of years or less. International drilling efforts may incorporate drilling by alternative vessels, such as drilling in the Arctic Ocean, one of the frontiers in ocean science, and drilling from platforms in shallower ocean regions than are accessible to the present drilling vessel. If these ambitious programs are indeed carried out, we can expect to learn much more about the working of the Earth's system of lithosphere–ocean–atmosphere–biosphere, specifically about the sensitivity of the climate system to changes, about the controls on the long-term evolution of this sensitivity, and about the complex interactions of the biospheric, lithospheric, oceanic, and atmospheric components of the Earth system at various timescales.

See also

Abrupt Climate Change. Authigenic Deposits. Benthic Foraminifera. Calcium Carbonates. Cenozoic Climate – Oxygen Isotope Evidence. Cenozoic Oceans – Carbon Cycle Models. Clay Mineralogy. Deep-sea Drilling Methodology. Deep-sea Drilling Results. El Niño Southern Oscillation (ENSO). Geomagnetic Polarity Timescale. Holocene Climate Variability. Igneous Provinces. Methane Hydrates and Climatic Effects. Methane Hydrates. Mid-ocean Ridge Geochemistry and Petrology. Millenial Scale Climate Variability. Monsoons, History of. North Atlantic Oscillation (NAO). Ocean Margin Sediments. Orbitally Tuned Timescales. Paleoceanography, Climate Models in. Past Climate From Corals. Pelagic Biogeography. Pore Water Chemistry. Propagating Rifts and Microplates. Protozoa, Planktonic Foraminifera. Protozoa, Radiolarians. Sea Level Variations Over Geologic Time. Sea Level Change. Seamounts and Off-ridge Volcanism. Sedimentary Record, Reconstruction of Productivity from the. Sediment Chronologies. Thermohaline Circulation.

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PALEOCEANOGRAPHY, CLIMATE MODELS IN

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Introduction

Climate models have been applied to the investigation of ancient climates for about 25 years. The early investigations used simple energy balance models, but since the 1970s increasingly more elaborate atmospheric general circulation models (AGCMs) have been applied to paleoclimate problems. It is only within the last decade that climate model results have been used to drive ocean circulation models to simulate the behavior of ancient oceans. Similarly, increasingly more complex ocean models have been used since the 1970s to explore the effects of changing boundary conditions on ocean circulation and climate. The early paleo-ocean models were driven by modern winds and hydrologic cycle data; the more recent simulations use paleoclimate-model-generated data. In some of the early models sea surface temperatures were specified, but this locks the model to a particular solution. Runoff from land has only been included in the most recent models. Experiments with coupled atmosphere–ocean models are just beginning.

Paleo-ocean modeling has been directed largely towards trying to understand two major problems related to possible changes in ocean heat transport with global climatic implications: (1) the origin of the Late Cenozoic glacial ages, with special attention to the initiation and cessation or slowdown of the 'Global Conveyor System,' and (2) the warm climates of the Late Mesozoic and Eocene, with low meridional temperature gradients. One group of modeling exercises has concentrated on the effects of interocean connections, particularly on the effects of opening and closing of gateways between the major ocean basins on the global thermohaline circulation system. Another major set of investigations has focused on ocean surface and thermohaline circulation on a warm Earth, with higher concentrations of atmospheric CO_2 and the very different paleogeography of the Late Mesozoic.

Ocean Gateways and Climate

The effects of interocean gateways on ocean circulation and the global climate system have been a matter of speculation since the late 1960s and of experimentation via box models and numerical simulation since the 1980s. **Figure 1** shows the major gateways that have opened or closed during the Cenozoic. In most instances the timing of opening or closing of gateways has been deduced from the regional plate tectonic context, but has an uncertainty of a few million years. In some cases, such as the opening of passages between Australia, South America and Antarctica the plate tectonic record is ambiguous and the timing is inferred from climate change in the surrounding regions. For a few passages, such as Panama and Gibraltar, the timing is known to within a few tens of thousands of years because the resulting oceanographic changes are reflected in ocean floor sediments on either side of the gateway. Until now it has been possible to explore the importance of only a few of the most critical gateways for the global climate system. Most of these investigations have concentrated on exploring the role of salinity in forcing the thermohaline circulation to develop an understanding of the behavior of the 'Great Conveyor.' The term 'Great Conveyor' is used to describe the global thermohaline circulation that starts with sinking of cold saline water in the Norwegian–Greenland Sea and continues southward as the North Atlantic Deep Water (NADW). On reaching the Southern Ocean, it is supplemented by water sinking in the region of the Weddell Sea. The deep water then flows into the Indian and Pacific Oceans where it returns to the surface. The return surface flow is then from the Pacific through

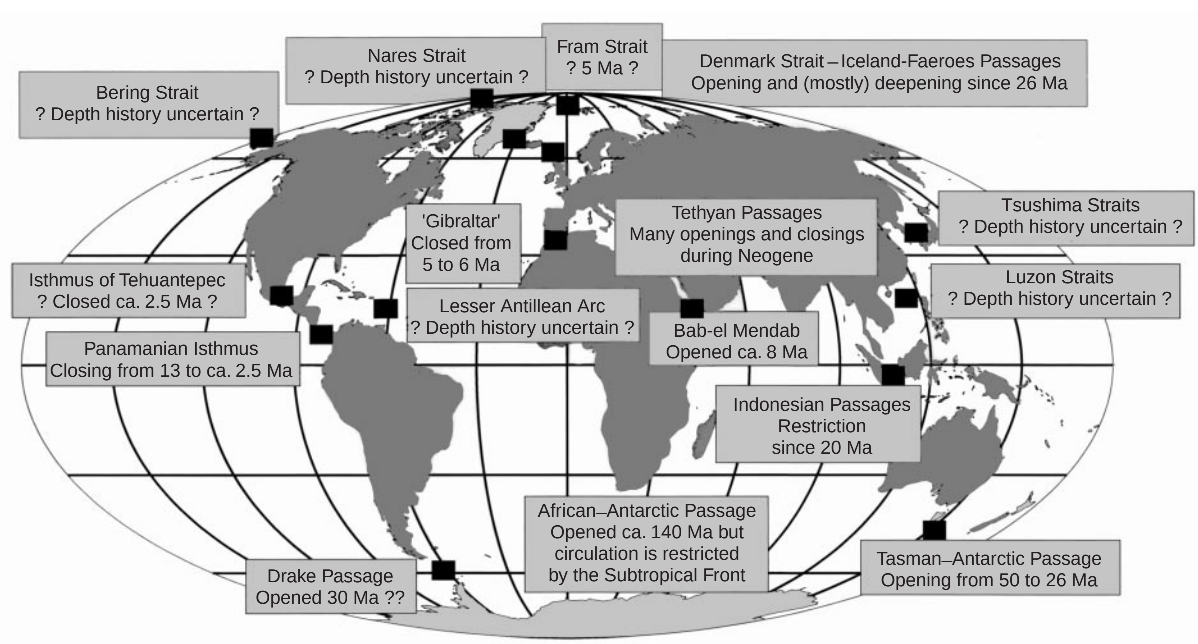

Figure 1 Interocean gateways which have opened or closed during the Cenozoic (since 65 Ma).

the Indonesian Passages and across the Indian Ocean, then around South Africa into the South Atlantic and finally northward to the Norwegian–Greenland Sea. Paleoceanographic data show that the production of NADW has slowed or even stopped from time to time. This has major implications for the paleoclimate of the continents surrounding the North Atlantic because it is the sinking of water in the Norwegian–Greenland Sea that draws warm surface waters northward along the western margin of Europe and Scandinavia.

It has been argued on the basis of simple model calculations that the Atlantic acts as a salt oscillator. The southward flow of NADW is thought to export salt from the North Atlantic. When so much salt has been exported that the surface waters are no longer so saline, deep water formation in the Norwegian–Greenland Sea will stop, shutting down the Global Conveyor. The Global Conveyor is revived by the loss of water from the Atlantic to the Pacific through the atmosphere across Central America. This increases the salinity of the North Atlantic to levels where the deep water formation is initiated again.

It has also been suggested that the saline Mediterranean outflow is an important forcing factor controlling the generation of NADW. Some of the Mediterranean outflow water becomes entrained in the surface waters crossing the Iceland–Scotland Ridge, raising the salinity to a level that can promote sinking as the water cools.

The salinity control hypothesis has been questioned by authors who argue that the global thermohaline circulation system is driven by Southern Hemisphere winds, and that the salinity difference between the Atlantic and Pacific plays only a minor role. This conclusion is based on an idealized ocean general circulation model (OGCM) using the simple geometry of two polar continents connected by a long thin meridional land mass. The model has no salinity forcing or sea ice formation, and no separate Atlantic Basin. The ocean model is coupled to a simple energy balance atmosphere with imposed zonal winds. Removing a piece of the land mass at the latitude of the Drake Passage induces an interhemispheric conveyor, similar to the modern Great Conveyor, which warms the entire Northern Hemisphere by several degrees. In this case, the conveyor is driven by the Southern Hemisphere winds and salinity plays no role at all.

Both of these models are great oversimplifications of the real world. They raise the question of whether the same results will be obtained with simulations having more realistic geographic boundary conditions, wind forcing, and radiative balance.

Drake Passage

Paleoceanographers have assumed that the opening of the Tasman–Antarctic Passage and subsequent opening of the Drake Passage led to isolation of the Antarctic continent. It has been argued that this resulted in a sharp meridional thermal gradient across the Southern Ocean and promoted the glaciation of the Antarctic continent.

The importance of the Drake Passage for the modern thermohaline circulation has been recognized by physical oceanographers since 1971 when scientists at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey used an early OGCM to experiment with a closed Drake Passage. They found that closure of the passage would increase the outflow of Antarctic Bottom Water (AABW) to the world ocean. The same result has been obtained for the effect of closure of the Drake Passage using other ocean models. It has been concluded that the opening of the Drake Passage was responsible for creating the circulation system we observe today.

Isthmus of Panama

Another important event affecting Earth's climate history was the closure of the connection between the Atlantic and Pacific across Central America. It has long been suspected that this paleographic change set the stage for the Northern Hemisphere glaciation.

Workers at the Max Planck Institute for Meteorology in Hamburg, explored the effects of an open Central American Passage using a model with a $3.5^\circ \times 3.5^\circ$ grid with 11 vertical levels, realistic bottom topography, and a full seasonal cycle. Although it does not simulate mesoscale eddies, the Hamburg OGCM does well at simulating the present surface and deep circulation of the ocean. A Central American Passage was opened between Yucatan and South America, and a sill depth of 2711 m was specified. The simulation was forced by the modern observed wind stress field and air temperatures. The large-scale low-latitude interchanges of waters between the Atlantic and Pacific had dramatic effects. The regional slope on the ocean surface from the western Pacific to the Norwegian–Greenland Sea was reduced. Flow through the Central American Passage was 1 Sv ($1\ \mathrm{Sv} = 10^6\ \mathrm{m^3\ s^{-1}}$) of wind-driven surface water from Atlantic to Pacific and 10 Sv of subsurface water driven by the hydrostatic head from Pacific to Atlantic. Flow through the Bering Strait, presently from the Pacific to the Arctic, was reversed, with a low salinity outflow from the Arctic into the North Pacific. There was little effect on flow through the Drake Passage. The salinity difference between the Atlantic and Pacific was greatly reduced. The production of NADW ceased, and flow of the Gulf Stream was reduced whereas flow of the Brazil Current was enhanced. The outflow of AABW into the world ocean increased about 25% with the closed Central American Passage. Southward oceanic heat transport also increased by about 25%, as more warm water from the South Atlantic was drawn southward to replace the surface water sinking in the Weddell Sea to form AABW. These changes would have major implications for global climates, making Europe colder and providing a larger snow source for the Antarctic. The results of this experiment did much to stimulate further studies.

The extreme sensitivity of the Atlantic thermohaline circulation to an open or closed Panama Strait has not been borne out by more realistic coupled atmosphere–ocean models (AOGCM). A subsequent experiment found a critical threshold for water transport through the passage affecting formation of NADW. Flows up to 5 Sv from the Pacific to the Atlantic through the passage still allow NADW to form, but at a rate only about 50% that of the present day. Greater flows shut down the NADW production.

In contrast, a recent AOGCM simulation using the recently developed Fanning and Weaver atmospheric energy-moisture balance model indicated that NADW formation could take place even with a fully open passage through Panama.

Combined Opening and Closure of the Drake and Panama Passages

One set of experiments has combined the effect of closing the Drake Passage and opening Panama. Two scenarios were examined, a closed Drake Passage and closed Central American Passage, and a closed Drake Passage with an open Central American Passage. Atmospheric forcing of the ocean model was with present day winds. The results are summarized in **Figure 2**.

During the past 60 million years the Drake and Central American Passages have not been closed at the same time. Nevertheless, it is an interesting experiment to examine the effect of a pole-to-pole meridional seaway connected to the world ocean through a high latitude passage on the east (between Africa and Antarctica). The major effect of this configuration was to increase the outflow of AABW to the world ocean by a factor of four and suppress NADW production. The net effect is a doubling of the global rate of thermohaline overturning. Enhanced upwelling of AABW in the northern Atlantic reduced the salinity of the surface waters there, preventing formation of deep water.

The scenario with a closed Drake Passage and open Central American Passage corresponds to the paleogeography of the Atlantic from mid-Cretaceous through most of the Oligocene. The result of the experiment was similar to that closing both passages, except that the increase in AABW was less, about 3.2 times that at present. Production of NADW was suppressed, but the overall thermohaline circulation increased. In the South Atlantic,

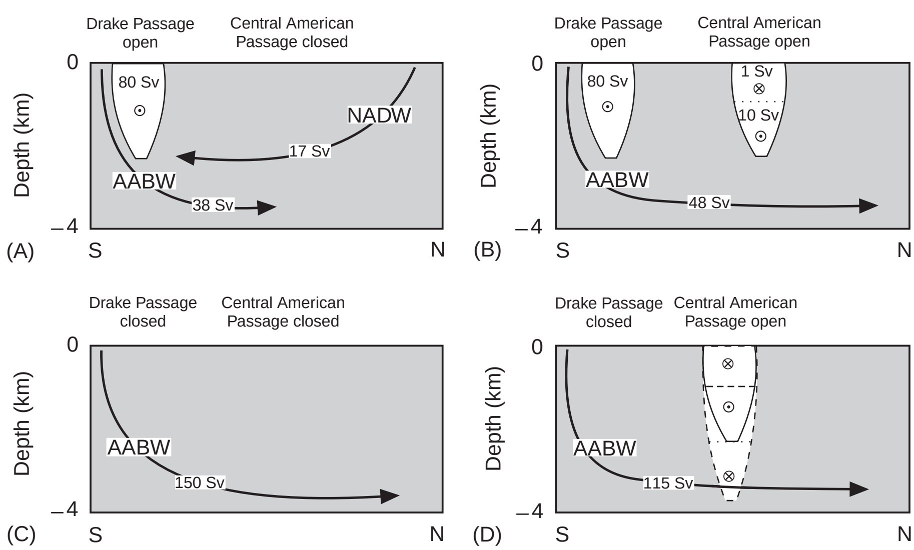

Figure 2 Pacific to Atlantic flow with open and closed Panama and Drake Passages. (After Mikalojewicz *et al.* 1993.) ⊙ = flow from Pacific to Atlantic. ⊗ = flow from Atlantic to Pacific. Volume fluxes in Sverdrups (Sv).

the deep waters were cooler and the thermocline weaker, promoting overturning and cooling of the surface waters. The flow of the Brazil Current was increased and the flow of the North Equatorial Current along the northern margin of South America was reduced. There was reduced equatorward transport in the eastern South Pacific and reduced flow of the Pacific western boundary current. The most controversial result of this experiment was that analysis of the surface heat flux suggested that the opening of the Drake Passage did not result in temperature changes large enough to have triggered Antarctic glaciation.

The effects of different widths of the Central American Passage and different sill depths in the Drake and Central American Passages were also investigated. It was found that widening the low latitude passage by removing all of Central America has little effect. A shallow sill (700 m) in the Drake Passage produced effects intermediate between experiments with deep sill (2700 m) used for the control run and the closed Drake Passage run. An experiment was also conducted with a deep (2700 m) Drake Passage and a very deep (4100 m) Central American Passage. The very deep Central American Passage allowed AABW flowing northward from the strong source in the Weddell Sea to enter the Pacific Basins, resulting in a reversal of the deep circulation in the Pacific. The flow of the western boundary current in the South Pacific reversed from northward (present) to southward.

Another experiment with the idealized OGCM explored the effect of making a gap in the northern hemisphere in the latitude band of the easterly trade winds. This corresponds roughly to a closed Drake Passage and an open Panama Passage. It was found that this produced an overturning circulation that cooled the tropics and warmed the high latitudes.

Gibraltar

Although it has been proposed that the saline outflow from the Mediterranean may play a critical role in the formation of NADW, ocean models do not support this idea. The influence of the Mediterranean outflow on the thermohaline circulation in the Atlantic has been investigated using modern boundary conditions in OGCMs. The opening and closing of the Straits of Gibraltar have been modeled by turning a 'salt source' at Gibraltar on and off.

One simulation indicates that open Straits of Gibraltar have only a minor effect on NADW production. Compared with closed Straits, the open Straits scenario increased the export of NADW from the North Atlantic by about 1 Sv.

Indonesian–Malaysian Passages

The connection between the Pacific and Indian Oceans through the Indonesian region is a critical part of the Great Conveyor. The passages through this region have become increasingly restricted as the Australian Block moves northward and collides with south-east Asia. Unfortunately, few model experiments have explored the effect on global ocean circulation.

OGCM sensitivity experiments suggest that closing these passages up to the level of the thermocline would cool the Indian Ocean about 1.5°C and warm the Pacific Ocean about 0.5°C. The model results also indicate that the influence of these passages on the production of NADW is very small.

Denmark Strait

The Denmark Strait, between Greenland and Iceland, is thought to play a critical role in the formation of NADW. The main body of cold saline intermediate water from the Norwegian–Greenland Sea flows into the North Atlantic through the Denmark Strait. In the North Atlantic it mixes with other waters to form NADW.

Experiments with a medium resolution OGCM indicated that the North Atlantic circulation is very sensitive to relatively small changes in the depth of the Denmark Strait.

Implications for the Global Climate Systems

Changes in the magnitude of the thermohaline circulation of the scale suggested by the circulation experiments exploring changes in interocean gateways have profound implications for the global climate system. On a planetary scale, the ocean and atmosphere carry roughly equal amounts of energy poleward, but their relative importance varies with latitude. The ocean dominates by a factor of two at low latitudes, and the atmosphere dominates by a similar amount at high latitudes. The present poleward ocean heat transport is estimated to reach a maximum of about 3.5×10^{15} W at 25°N and 2.7×10^{15} W at 25°S. The subtropical convergences act as barriers to poleward heat transport by the ocean. Only where deep water forms at high latitudes are warm subtropical waters drawn across the frontal systems to higher latitudes to replace the sinking waters.

If the entire thermohaline circulation were involved in the heat exchange between the polar and tropical regions, there would be an equatorward flow of 55 Sv warmed by about 15°C as it returns to the surface through diffuse upwelling. This is equal to an energy transport of 3.5×10^{15} W, about half the total surface ocean transport at low latitudes. Clearly, the transport of heat by the thermohaline system is an important component of the ocean transport system. The great increases in production of polar bottom waters indicated by the closed Drake Passage models suggest that in earlier times ocean heat transport may have dominated the earth's energy redistribution system.

Ocean Circulation on a Warm Earth

During the Late Cretaceous and Eocene, the Earth was characterized by warm polar regions with mean annual temperatures well above freezing and perhaps as warm as 10°C. A major controversy has arisen as to whether increased ocean heat transport played a role in creating these conditions. It has been suggested that there may have been a reversal of the thermohaline circulation, with sinking of warm saline waters in low latitudes and upwelling of warm waters in the polar regions. A secondary question has concerned the effect of the very different paleogeography, with the low latitude circumglobal Tethys seaway connecting the Atlantic and Pacific Oceans, on ocean circulation.

The Ocean Heat Transport Problem

The role of ocean heat transport in producing global warmth has been assessed by using the US National Center for Atmospheric Research (NCAR) Community Climate Model 1 (CCM1) AGCM with present-day geography, but with a swamp ocean. Swamp oceans were used in many early climate models; they have no heat storage capacity and do not transport heat, but serve as a source of moisture. Simulating a world without ocean currents, it was found that polar temperatures were 5–15°C warmer than observed today. Tropical temperatures were about 2°C less. An experiment with the Princeton model used idealized geography, a single ocean and a wedge-shaped continent extending from pole to pole for two AGCM experiments, one with and one without ocean heat transport. The experiment with ocean heat transport produced surface air temperatures poleward of 50° that were 20°C warmer than in the experiment without ocean heat transport. Subsequently, the meridional ocean heat transport required to maintain polar ocean surface temperatures at 10°C was determined. If the ocean were solely responsible, such warm polar temperatures would require implausible ocean heat transports of 2.3×10^{15} W across the Arctic Circle, implying water volume fluxes in excess of 100 Sv, or over twice the flow of the Gulf Stream today.

In a discussion of the role of ocean heat transport in paleoclimatology it has been argued that theoretical arguments as well as simple models suggest that the total poleward transport of energy is not dependent on the structure of either the atmosphere or ocean. Changes in one transport mechanism tend to be compensated by a change in the opposite sense in the other, so that the total transport remains constant. Apparently only extreme changes in the geography of the polar regions can cause uncompensated changes in poleward heat transport. By using the NCAR CCM1 AGCM linked with a slab mixed-layer ocean model, three experiments reflecting different amounts of ocean heat transport have been conducted. Doubling the present flux and reducing the flux to zero resulted in global average temperatures of 14.4 and 15.9°C, respectively compared with the present 15°C. The major effect of changing the ocean heat flux through this range was to lower tropical temperatures 5°C while making only a small increase in polar temperatures.

By using NASA's Goddard Institute of Space Science (GISS) AGCM with slab ocean to calculate the ocean heat transport required to achieve specific sea surface temperatures it was concluded that a 46% increase in ocean heat transport was required to produce a planetary warming of 6°C, which was assumed to be typical for the Jurassic, and that a 68% increase could produce a warming of 6.5°C, assumed to be typical for the Cretaceous. The reduced sea ice formation and ice–albedo feedback in response to the increased poleward heat transport were considered critical factors.

Surface and Thermohaline Circulation

In 1972 the first attempt was made to simulate Late Cretaceous ocean circulation using an analog model. An experiment was carried out using a large water-filled rotating dish set up with continental blocks in a Cretaceous configuration, with wind stress applied to the surface by fans, assuming a poleward displacement of the winds by 10–15°. This analog model produced large anticyclonic gyres in the Pacific and east to west flow through the Tethys, a pattern widely reproduced in paleo-oceanographic studies (**Figure 3**).

In the late 1980s an OGCM was used to perform experiments on ocean circulation with mid-Cretaceous paleogeography. Two of the models contrasted the effects of the different temperatures and winds generated by AGCMs assuming present day and four times present day atmospheric CO_2 concentrations. The present-day CO_2 experiment showed eastward flow across the Gulf of Mexico, westward flow through the Caribbean, a broad west

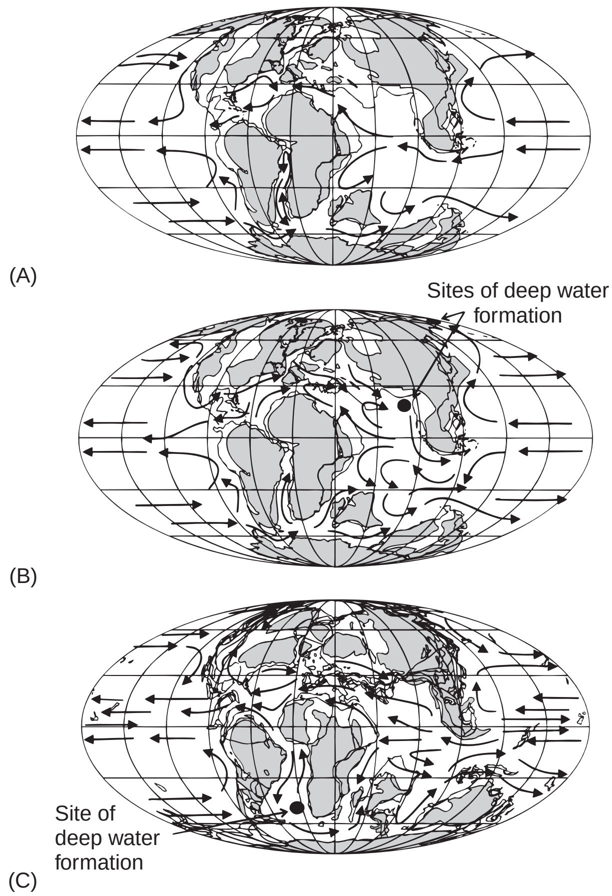

Figure 3 Three models of Late Cretaceous Ocean circulation. (A) After the analog model of Luyendyk *et al.* (1972). (B) After the OGCM of Barron *et al.* (1993). (C) After the OGCM of Brady *et al.* (1998). Note the different directions of flow through the Tethyan circumglobal seaway.

to east current through the western Atlantic, and a clockwise anticyclonic gyre between Eurasia and Africa. Strong western boundary currents developed along the margins of Asia, Africa, and India. The current off north-east Asia continued into the Arctic to a high-latitude site of deep water formation. The thermohaline circulation indicated a strong polar source north of east Asia, and a weak source in the eastern Tethys. For the four-times present CO_2 experiment surface currents in the tropics and subtropics were similar to those in the first experiment, but the flow of the western boundary current off north-east Asia no longer continued into the Arctic. The thermohaline circulation was completely different, lacking a polar source of deep water, but having a strong source in the eastern Tethys which produced a deep flow south and eastward into the Pacific basin.

A simulation of Late Cretaceous ocean circulation using higher spatial resolution and driven by a later version of the GENESIS Earth System Model suggested that low latitude deep water formation may be more complex than had been thought. The model suggested four potential sites of warm saline dense water formation along the borders of the Tethys and off western South America. However, at three of these sites the water sank only to upper intermediate levels. However, at a site north of the equator on the west African margin the water sank first to an intermediate level, then spread south to the subtropical front where it sank further into the deep ocean interior and flowed out through the Indian Ocean into the Pacific.

Models of Seaways

There have been some model simulations of circulation in shallow continental-scale ocean passages, such as the Cretaceous Western Interior Seaway of North America and the Miocene Tethys–Paratethys connection. These simulations are not based on general ocean models, but use circulation models developed for study of estuaries and tides. They may include tidal currents and simulate flows resulting from salinity differences induced by runoff from land.

Verification of Ocean Models

It is not easy to test the results of a paleoceanographic simulation against observations. The simplest tests have been to use palaeontologic and sedimentologic data to confirm or reject the direction of major current systems. Much geologic evidence suggests that flow through the Tethys was east to west, but some model simulations indicate that it was west to east, others that it was east to west.

Several recent attempts have been made to compare oxygen isotopic data with the temperatures and salinities predicted by the paleo-oceanographic simulations, but there is uncertainty about how to correct for the isotopic differences due to salinity because of the complexity of the relation to the hydrologic cycle. The solution will ultimately lie in incorporating isotopic fractionation into the ocean models.

Conclusions

The use of models to investigate the relations between ancient climates and ocean circulation is still in its infancy. There have been few comparisons of different models using the same boundary conditions. The results produced by different OGCMs for similar boundary conditions are often significantly different. In spite of the different model results it has become clear that the opening and closing of passages between the major ocean basins have had a major effect on the Earth's climate. Attempts to simulate ocean circulation on a warm Earth indicate that sites of deep water formation may shift to low latitudes when atmospheric CO_2 concentrations are high.

See also

Abrupt Climate Change. Cenozoic Climate – Oxygen Isotope Evidence. Elemental Distribution: Overview. Heat Transport and Climate. Thermohaline Circulation.

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