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MONSOONS, HISTORY OF

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Introduction

The difference in specific heat capacity between continents and oceans (and specifically between the large Asian Continent and the Indian Ocean) induces the monsoons, strong seasonal fluctuations in wind direction and precipitation over oceans and continents. Over the Indian Ocean, strong winds blow from the south-west during boreal summer, whereas weaker winds from the north-east blow during boreal winter. The monsoons are strongest over the western part of the Indian Ocean and the Arabian Sea (**Figure 1**). The high seasonal variability affects various fluctuations in the environment and its biota which are reflected in marine sediments. Marine sedimentary sequences from the continental margins thus contain a record of the history of monsoonal occurrence and intensity, which may be deciphered to obtain insight in the history of the monsoon system. Such insight is important not only to understand the mechanisms that cause monsoons, but also to understand the influence of monsoons on the global climate system including the Walker circulation, the large-scale, west–east circulation over the tropical ocean associated with convection. The summer monsoons may influence the Southern Oscillation because of interactions between the monsoons and the Pacific trade wind systems.

Geologic Records of the Monsoons

Sedimentary sequences record the effects of the monsoons. One such effect is the upwelling of deeper waters to the surface, induced by the strong southwesterly winds in boreal summer in the Arabian Sea, and the associated high productivity of planktonic organisms. Continents supply sediments to the continental margin through the discharge of rivers, as the result of coastal erosion, and carried by winds (eolian sediments). Monsoon-driven wind direction and strength and precipitation therefore control the sediment-supply to the continental margin.

Monsoonal precipitation supplies a large volume of fresh water, discharged by rivers from the conti-

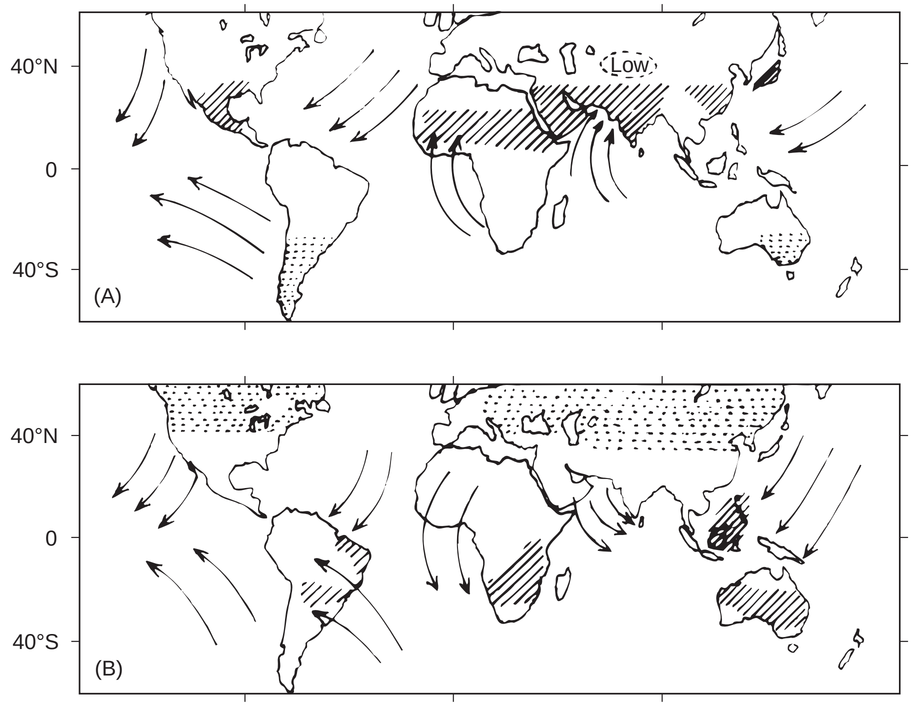

Figure 1 The domains of the monsoon system of the atmosphere during northern hemisphere (A) summer (B) winter. The hatching shows the land areas with maximum surface temperature and stippling indicates the coldest land surface.

nents into the oceans, with the flow directed by the topography in the regions of the river mouths. The density of fresh water is less than that of sea water, and the seasonal freshwater flow dilutes surface ocean water which then has a lower density than average sea water. The existence of strong vertical density gradients causes the development of stratification in the water column.

The elevation of the continent governs the circulation of the atmosphere, and influences vegetation patterns. The vegetation cover on the continent directly affects the albedo and heat capacity of the land surface, both of which are important factors in the generation of monsoonal circulation patterns. The high Himalayan mountain range acts as barrier for air circulation; east–west oriented mountain ranges particularly affect the course of the Jet Stream. Continental topography, vegetation coverage and elevation thus affect the monsoonal circulation and therefore the rate of sediment supply to the continental margin, as well as the composition of continental margin sedimentary sequences.

Sedimentary Indicators of Monsoons

Monsoon-induced seasonal contrasts in wind direction and precipitation are recorded in the sediments by many different proxies. Most of these monsoonal indicators, however, record qualitative and/or quantitative changes of the monsoons in one, but not in both seasons. For example, upwelling indicators in the Arabian Sea represent the strength of the south-west (summer) monsoon.

In interpreting the sedimentary record, one must note that bottom-dwelling fauna bioturbates the sediment to depths of about 10 cm, causing the co-occurrence of sedimentary material deposited at different times within a single sediment sample. Laminated sediments without bioturbation are only deposited in oxygen-minimum zones, where anoxia prevents activity of burrowing metazoa. The time resolution of studies of various monsoonal indicators thus is limited by this depth of bioturbation, but each proxy by itself does record information on the environment in which it formed at the time that it was produced. Single-shell measurements of oxygen and carbon isotopes in foraminiferal tests (see below) thus may show the variability within each sample, thus within the zone of sediment mixing.

Oxygen isotopes The oxygen isotopic ratio ($\delta^{18}O$) of the calcareous tests of fossil organisms (such as foraminifera) provides information on the oxygen isotopic ratio in sea water and on the temperature of formation of the test. The volume of the polar ice sheets and the local influx of fresh water controls the oxygen isotopic ratio of sea water. The $\delta^{18}O$ record of the volume of the polar ice sheets can be used for global correlation of oxygen isotopic stages, corresponding to glacial and interglacial intervals. Freshwater discharge caused by monsoonal precipitation lowers the $\delta^{18}O$ value of sea water. The temperature record of various species with different depth habits, such as benthic species at the bottom, and planktonic species at various depths below the surface, can provide a temperature profile of the water column. Temperature is the most basic physical parameter, which provides information on the stratification or mixing of the water column, as well as on changes in thermocline depth. Different species of planktonic foraminifera grow in different seasons, and temperatures derived from the oxygen isotopic composition of their tests thus delineates the seasonal monsoonal variation in sea surface temperatures.

Carbon isotopes The carbon isotopic ratio in the calcareous test of foraminifera provides information on the carbon isotopic ratio of dissolved inorganic carbon (DIC) in sea water and on biofractionation during test formation. Carbon isotopic ratios of various species of foraminifera which live at different depths provide information on the carbon isotopic profile of DIC in the water column. The carbon isotope ratio of DIC in sea water is well correlated with the nutrient concentration in the water, because algae preferentially extract both the lighter carbon isotope (^{12}C) and nutrients to form organic matter by photosynthesis. Decomposition of organic matter releases lighter carbon as well as nutrients, and lowers the carbon isotopic composition of DIC. The carbon isotopic profile with depth thus provides information on the balance of photosynthesis and decomposition.

Rate of sedimentation Marine sediments are composed of biogenic material produced in the water column (dominantly calcium carbonate and opal), and terrigenous material supplied from the continents. The sediments are transported laterally on the seafloor and down the continental slope, and eventually settle in topographic depressions in the seafloor. Both seafloor topography and the supply of biogenic and lithogenic material control the apparent rate of sedimentation.

Organic carbon content Organisms produce organic carbon in the euphotic zone, which is strongly recycled by organisms in the upper waters, but a small percentage of the organic material eventually settles on the seafloor. Organisms (including bacteria) decompose the organic carbon on the surface of the seafloor as well as within the sediment, using dissolved oxygen in the process. The flux of organic matter and the availability of oxygen thus control the organic carbon content in the sediments. In high productivity areas, such as regions where monsoon-induced upwelling occurs, a large amount of organic matter sinks from the sea surface through the water column. The sinking organic matter decomposes and consumes dissolved oxygen, and at mid-water depths an oxygen minimum zone may develop in such high productivity zones. Oxygen concentrations may fall to zero in high productivity environments, and in these anoxic environments, eukaryotic benthic life becomes impossible, so that there is no bioturbation. The organic carbon content in the sediment deposited below oxygen minimum zones may become very high, and values of up to 7% organic carbon have been recorded in areas with intense upwelling, such as the Oman Margin.

Calcium carbonate Three factors control the calcium carbonate content of pelagic sediments: productivity, dilution and dissolution. Calcium carbonate tests are produced by pelagic organisms, including photosynthesizing calcareous nannoplankton and heterotrophic planktonic foraminifera. At shallow water depths (above the calcium carbonate compensation depth, CCD) dissolution is negligible, therefore, the calcium carbonate content in continental margin sediments is regulated by a combination of biotic productivity and dilution by terrigenous sediment.

Magnetic susceptibility Magnetic susceptibility provides information about the terrigenous material supply and its source. The part of the sediment provided by biotic productivity (calcium carbonate and opaline silica) has no carriers of magnetic material. Magnetic susceptibility is thus used as an indicator of terrigenous supply to the ocean.

Clay mineral composition Weathering and erosion processes on land lead to the formation of various clay minerals. The clay mineral composition in the sediments is an indicator for the intensity of weathering processes and thus temperature and humidity in the region of origin. The clay mineral composition thus can be used as a proxy for the aridity and vegetation coverage in the continents from which the material derived. In addition, the crystallinity of the clay mineral illite depends on the moisture content of soils in the area of origin. At high moisture, illite decomposes and dehydrates, so that its crystallinity decreases. Therefore, the crystallinity of illite can be used as a proxy for the humidity in its source area.

Eolian dust Eolian dust consists of fine-grained quartz and clay minerals, such as illite. The content and grain-size of eolian dust in marine sediment, therefore, is an indicator of wind strength and direction, as well as of the aridity in the source area.

Fossil abundance and diversity The abundance and diversity of foraminifera, calcareous nannoplankton, diatoms and radiolarians depend on the chemical and physical environmental conditions in the oceans. The diversity of nannofossil assemblages decreases with sea surface temperature and is thus generally correlated with latitude. In upwelling areas, low sea surface temperatures caused by the monsoon-driven upwelling disturb the zonal diversity patterns of nannoflora. Therefore, the diversity of nannofossils can be used as an upwelling indicator. In addition, the faunal and floral assemblages can be used to estimate sea surface temperature and salinity as well as productivity.

UK_{37} ratio The biomarker UK_{37} (an alkenone produced by calcareous nannoplankton) is used to estimate sea surface temperatures within the photic zone where the photosynthesizing algae dwell. The records are not always easy to calibrate, especially in the tropics and at high latitudes, but global calibrations are now available.

Indicators of Present Monsoons

The specific effect of the monsoons on the supply of lithogenic and biogenic material to the seafloor varies in different regions, so that specific tracers can not be efficiently applied in all oceans.

Arabian Sea

During the boreal summer, strong south-west monsoonal winds produce intense upwelling in the Arabian Sea (**Figure 2**). These upwelling waters are characterized by low temperatures and are highly enriched in nutrients. The process of upwelling fuels the biological productivity in June through August in the Arabian Sea. The weaker, dry, north-east winds which prevail during the boreal winter do not produce upwelling, and productivity is thus lower in the winter months. Thus, the south-west and north-east monsoonal winds produce a strong seasonal contrast in primary productivity in the Arabian Sea. Sediment trap mooring experiments have demonstrated that up to 70% of the biogenic and lithogenic flux to the seafloor occurs during the summer monsoon. Biological and terrestrial particles thus strongly reflect summer conditions, and eventually settle on the seafloor to contribute to a distinct biogeochemical record of monsoonal upwelling. Therefore, regional sediments beneath the areas affected by monsoon-driven upwelling record long-term variations in the strength and timing of the monsoonal circulation. The following proxies were used to study the upwelling strength in the Arabian Sea.

***Globigerina bulloides* abundance** Seasonal plankton tows and sedimentary trap data document that the planktonic foraminifer species *G. bulloides* is abundant during the summer upwelling season in the Arabian Sea. Core top data from the upwelling zones of the Arabian Sea show that the dominance of *G. bulloides* in the living assemblage is preserved in the sediment. Changes in the abundance of *G. bulloides* in the sediments thus have been used to infer the history of upwelling intensity in the western Indian Ocean.

Lithogenic material Lithogenic material deposited in the north-west Arabian Sea is dominantly eolian (diameter up to 18.5 μm), and is transported exclusively during the summer south-west monsoon. The lithogenic grain size in sediment cores thus provides information about the strength of the south-west monsoonal winds and associated upwelling in the Arabian Sea.

China Sea

The surface circulation patterns in the China Sea are also closely associated with the large-scale seasonal reversal of the atmospheric circulation over the Asian continent. High precipitation over Asia during the summer leads to increased input of fresh water into the China Sea, lowering sea surface salinity. Therefore, the $\delta^{18}O$ record of planktonic foraminifera in sediment cores documents the magnitude of freshwater discharge, sea surface salinity and summer monsoonal rainfall in the past. During the winter, the westerly winds lower the sea surface temperature and deliver a large amount of eolian dust to the South China Sea. The rate of eolian dust supply and sea surface temperature changes in this region thus reflect the strength of the winter monsoon.

Japan Sea

The winter monsoon's westerlies transport eolian dust from the Asian desert regions to the Japan Sea and the Japanese Islands 3–5 days after sandstorms in the source area. The thickness of the dust layer is

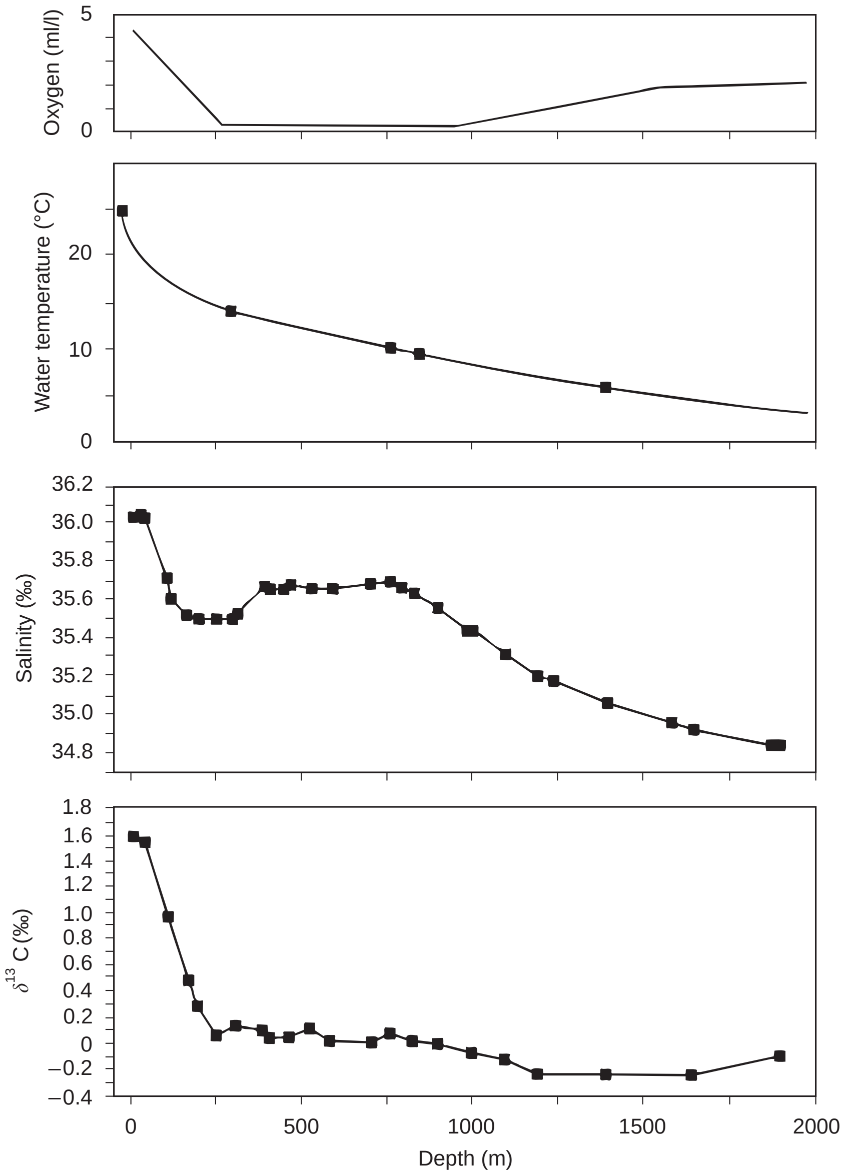

Figure 2 Vertical profiles of δ^{13}C, salinity, temperature and oxygen values in the Arabian Sea. δ^{13}C and salinity are from GEOSECS Station 413, water temperature and oxygen values are from ODP Site 723 in the Oman Margin.

larger in the western Japan Sea. The concentration and grain size of eolian particles in sediments of Japan Sea thus represents the strength of the winter monsoon.

Variability of Monsoons During Glacial and Interglacials

Arabian Sea

Along the Oman Margin of the Arabian Sea, strong south-west summer monsoon winds induce upwelling. Detailed analyses of various monsoon tracers such as abundance of *G. bulloides* and *Actinomma* spp. (a radiolarian) and pollen reveal that the south-west monsoon winds were more intense during interglacials (warm periods) and weaker during glacials (cold periods), recognized by the oxygen isotopic stratigraphy in the same samples.

Carbon isotope differences between planktonic and benthic foraminifera show lower gradients during interglacials, higher gradients during glacials. The lower gradients indicate that upwelling was strong (and pelagic productivity high) during interglacials due to a strong summer south-west monsoon. Similarly, the oxygen isotope difference between planktonic and benthic foraminifera along the Oman Margin reflects changes in thermocline

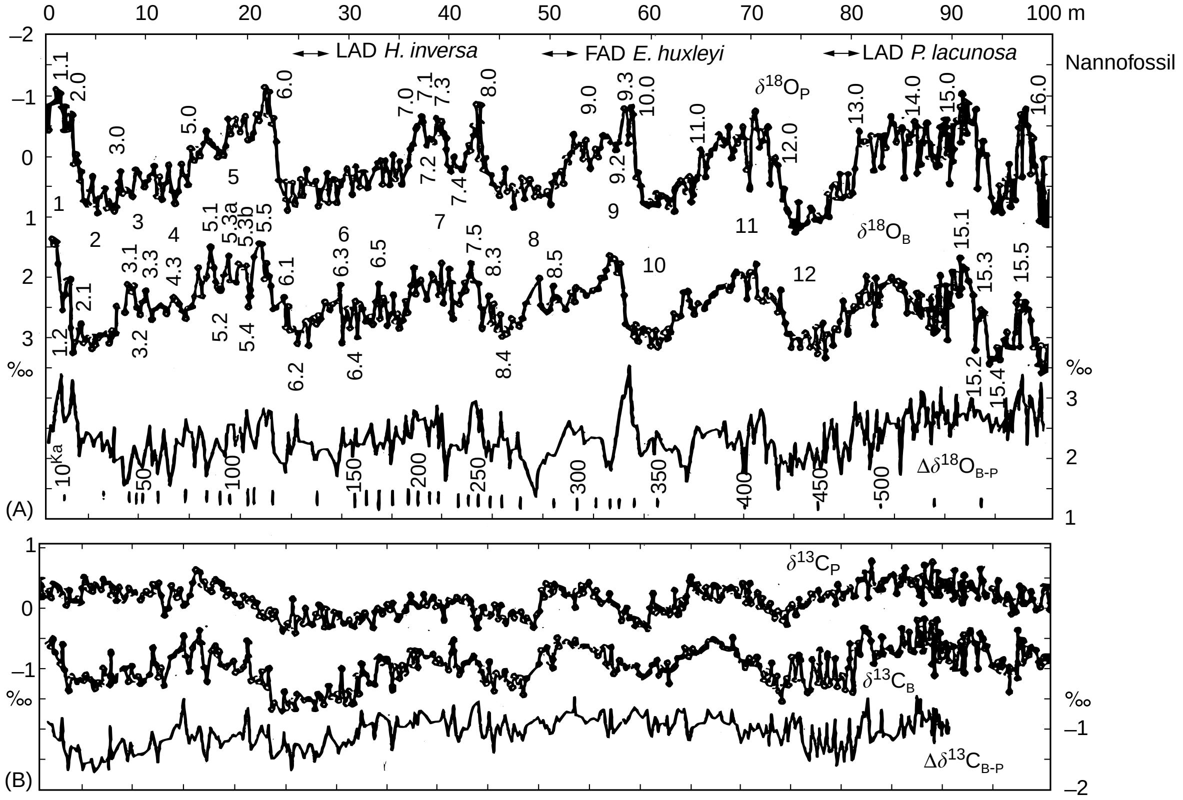

Figure 3 (A) Oxygen isotope profiles of planktonic foraminifera (*Pulleniatina obliquiloculata*, $\delta^{18}O_P$), and benthic foraminifera (*Uvigerina excellens*, $\delta^{18}O_B$) and the difference between oxygen isotopes of planktonic and benthic foraminifera ($\Delta\delta^{18}O_{B-P}$). (B) Carbon isotope profiles of planktonic foraminifera ($\delta^{13}C_P$) and benthic foraminifera ($\delta^{13}C_B$) and the difference between planktonic and benthic records ($\Delta\delta^{13}C_{B-P}$) over last 800 000 years at ODP Site 723 in the Arabian Sea. Large planktonic–benthic differences indicate a more vigorous monsoonal circulation during the summer monsoon.

depth, associated with summer monsoon-driven upwelling. A larger oxygen isotope difference between planktonic and benthic foraminifera during interglacials reflects the presence of a shallow thermocline, as a result of the strong summer monsoons. Oxygen and carbon isotope records from various planktonic and benthic foraminifera in several cores located within and away from the axis of the Somali Jet along the Oman Margin indicate that sea surface temperatures were lower and varied randomly during interglacials, reflecting strong upwelling induced by a strong summer monsoon (**Figure 3**).

Studies of the oxygen and carbon isotope composition of individual tests of planktonic foraminifera enable us to understand the seasonal temperature variability induced by monsoons in the Arabian Sea. Such studies show that the seasonality was stronger during glacials and weaker during interglacials, because during glacials the south-west summer monsoon was weaker and the north-east winter monsoon stronger. The variability in seasonal contrast during glacials and during interglacials suggests that interannual and interdecadal changes in monsoonal strength were also greater during glacial periods than during interglacials (**Figure 4**).

The average rate of sedimentation was higher during glacials than during interglacials, because the enhanced precipitation over the Arabian Peninsula during glacials caused enhanced transport of terrigenous material by rivers into the Arabian Sea. This high terrigenous supply during glacials was not caused by the low sea-level stands (and larger surface area of the continents), because the maximum terrigenous supply did not occur during the maximum phase of regression.

South China Sea

High-resolution studies in the South China Sea document a high rate of delivery of eolian dust during glacial periods, as well as lower sea surface temperatures, documented by the UK_{37} records. These data indicate that during glacial periods the winter monsoon was more intense. During interglacials the sea surface salinity (derived from oxygen isotope records) was much lower than during gla-

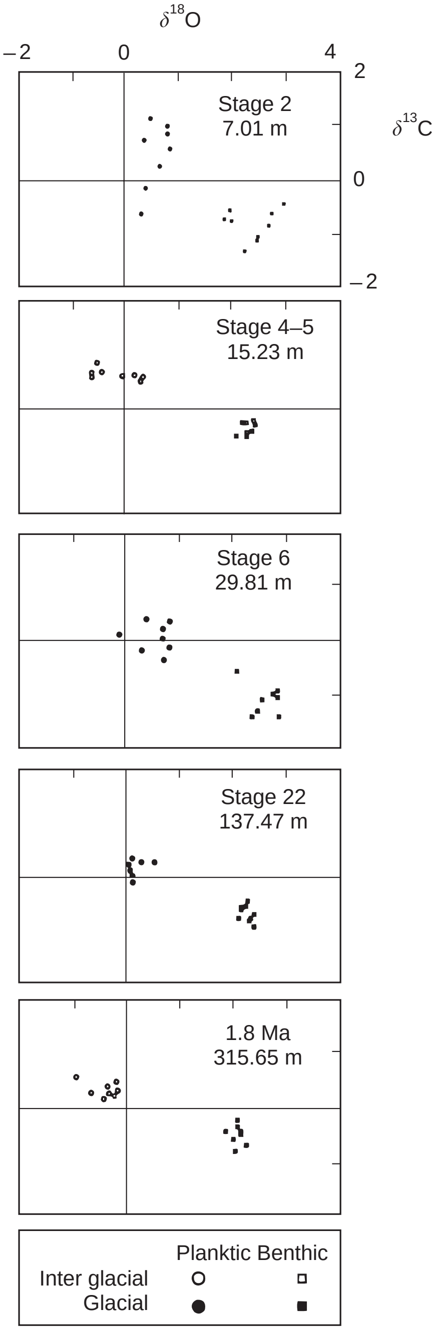

Figure 4 Carbon and oxygen isotope ratios of individual tests of planktonic foraminifera (*Pulleniatina obliquiloculata*) and benthic foraminifera (*Uvigerina excellens*) at ODP Site 723 in the Arabian Sea. The variations in difference between planktonic and benthic values reflect the magnitude of the seasonal changes in surface and bottom waters through time.

cials, probably as a result of increased freshwater discharge from rivers caused by the high summer monsoon precipitation. Over the South China Sea glacials were thus characterized by an intense winter monsoon, and interglacials by a strong summer monsoon circulation.

Japan Sea

The oceanographic conditions of the Japan Sea are strongly influenced by eustatic sea level changes, because shallow straits connect this sea to the Pacific Ocean. In glacial times, at low sea level, most of the straits were above sea level and the Japan Sea was connected to the ocean only by a narrow channel located on the present continental shelf. River discharge of fresh water into the semiisolated Japan Sea caused the development of strong stratification, and the development of anoxic conditions, as documented by the occurrence of annually laminated sediments.

The sedimentary sequence in the Japan Sea thus consists of mud, with laminated sections alternating with bioturbated, homogeneous muds. During interglacials the waters at the bottom were oxygenated, although the organic carbon content of the sediment can be high (up to 5%) and diatoms abundant (up to 30% volume). During glacials, conditions on the seafloor alternated between euxinic (anoxic) and noneuxinic. Glacial and interglacial parts of the sediment section can thus be easily recognized.

The sedimentary sequences contain eolian dust transported from the deserts of west China and the Chinese Loess Plateau by the westerly winter monsoon. The eolian dust content of the sediments is thus an indicator of the strength of the winter monsoon. The crystallinity of illite, a main component of the eolian dust, indicates that the source region on the Asian continent was more humid during interglacials. A high content of eolian dust and a high crystallinity of illite during glacial stages indicates that during these intervals the winter monsoon was strong and the summer monsoon weak. Summer monsoons were strong during interglacials, but winter monsoons were strong during glacials.

Long-term Evolution of the Asian Monsoon

Arabian Sea

Long-term variations of proxies of monsoonal intensity tracers, especially the species diversity of calcareous nanofossil species, and the abundance of the planktonic foraminifera *G. bulloides* and the radiolarian *Actinomma* spp. (upwelling indicators) show that the evolution of the Asian monsoon started in the late Miocene, at about 9.5 Ma (million years ago). Between 9.5 and 5 Ma the monsoon increased noticeably in strength, with smaller fluctuations in monsoonal intensity from 5 to 2 Ma (**Figure 5**).

Upwelling indicators such as the differences in oxygen and carbon isotope between planktonic

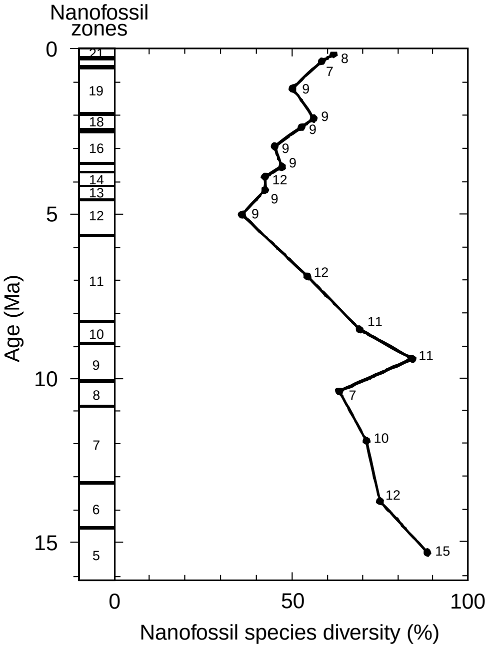

Figure 5 Calcareous nanofossil diversity for the last 15 Ma in the Indian Ocean. High diversity indicates weak upwelling and low diversity represents strong upwelling. The upwelling intensity is controlled by the strength of the summer monsoon winds over the Indian Ocean. The numbers on the species diversity profile represent number of species.

foraminifera, and the organic carbon content in sediments from the Oman Margin indicate that until about 0.8 Ma the summer monsoon was intense, as during interglacials. Oxygen and carbon isotope ratios in individual tests of planktonic and benthic foraminifera show that from 0.8 Ma onwards the strength of the summer monsoon changed with glacial and interglacial cycles, as described above.

China Sea

In sediments from the South China Sea magnetic susceptibility and calcium carbonate percentages started to decrease at about 7 Ma, reflecting increased deposition of terrigenous, eolian dust. This increase in dust supply indicates that monsoons started to become noticeable at that time. Both color reflectance and magnetic susceptibility show cyclic fluctuations in monsoonal intensity from 0.8 Ma on, in response to glacial and interglacial cycles (as described above).

Japan Sea

Cyclic changes with large amplitude of magnetic susceptibility and illite crystallinity in sediment cores indicate that the imprint of the monsoon signature in the Japan Sea sediment record started at about 0.8 Ma. The crystallinity of illite was much higher until 0.8 Ma, reflecting that the summer monsoon was weak until that time, as it was afterwards during glacials.

Asian Continent

Loess and paleosol sequences on the Chinese Plateau show cyclic fluctuations in magnetic susceptibility and illite crystallinity for the last 0.6 Ma. Loess and paleosol sequences in the Kathamandu Basin show cyclic fluctuations in magnetic susceptibility and illite crystallinity for the last 1.1 Ma. The cyclic sequences of low crystallinity, representing a humid climate in the interglacial periods in both areas, is consistent with the marine sediment records of the Japan Sea.

Palearctic elements first became represented in the molluskan faunas in the Siwalik Group sediments in the Himalayas after 8 Ma, suggesting the beginning of seasonal migrations of water birds crossing the Himalayas at this time. The diversity of this molluskan fauna increased around 5 Ma, a time when the summer monsoon was strong. The timing of developments in the molluskan faunas in the Himalayas is thus consistent with the long-term evolution of the Asian summer monsoon as derived from marine records.

The Asian Monsoon and the Global Climate System

Uplift of the Himalayas and the Tibetan Plateau occurred coeval with the increase in strength of the Asian Monsoon between 9.5 and 5 Ma, as documented by the heavy mineral composition of deposits in the Bengal Fan, derived from the weathering and erosion of the rising Himalayas. Cyclic fluctuations in the strength of the summer monsoon started at about 1.1 Ma in the southern Himalayas and Tibet, whereas in the Arabian Sea, South China Sea and Japan Sea such changes started at about 0.8 Ma.

Peru Margin

As a result of strong south-easterly trade winds, nutrient-rich water upwells along the Peru coast and reaches the photic zone in a belt that is approximately 10 km wide, and parallels the coast line. In this region, upwelling-induced productivity is very high. The organic carbon concentration in the sediments below this high-productivity zone has been used to trace the upwelling strength in the past. Upwelling is absent or less intense during El Niño Southern Oscillations events (ENSO), and the Southern Oscillation is linked to the Asian monsoons in the tropical Walker circulation.

Upwelling along the Peru Margin started at around 3.5 Ma, as indicated by an increase in the organic carbon content, and the decrease of sea surface temperatures (derived from UK_{37} records). Upwelling along the Peru Margin thus started after the Asian monsoons reached their full strength at about 5 Ma.

Equatorial Upwelling

The intensity of the South-east Asian monsoon controls the easterly trade winds associated with the north and south equatorial currents, and the strength of the easterly trade winds controls the intensity of equatorial upwelling. In the equatorial Pacific, the intensity of trade winds and equatorial upwelling increased at about 5 Ma (as indicated by a high abundance of siliceous and calcareous pelagic microfossils), at the time that the Asian monsoons developed their full intensity.

Conclusions

The evolution of the Asian monsoon started at around 9.5 Ma, in response to the uplift of the Himalayas. The monsoonal intensity reached its maximum at around 5 Ma, and from that time the associated easterly trade winds caused intense upwelling in the equatorial Pacific. Before 1.1 Ma, the summer monsoon was strong over the Arabian Sea, whereas the winter monsoon was strong over the Japan Sea. The glacial and interglacial cycles in intensity of the monsoons in the Arabian Sea, the South China Sea and the Japan Sea started around 0.8 Ma, coinciding with the uplift of the Himalayas to their present day elevation. Therefore, the chronological sequence of monsoonal events, and the strength of trade winds and equatorial upwelling suggests that the Asian monsoons (linked to the development of the Himalayan mountains) were an important control on global climate and oceanic productivity.

The tropics receive by far the most radiative energy from the Sun, and the energy received in these regions and the ways in which it is transported to higher latitudes controls global climate. In the tropics, the atmospheric circulation over the Asian continent is dominated by the area of highest elevation; the Himalayas and the Tibetan Plateau. The high heat capacity of this region causes the strong seasonality in wind directions, temperature, and rainfall, involving extensive transport of moisture and thus also latent heat from sea to land during summer. The Himalayas–Tibetan Plateau thus influence the transport of sensible and latent heat from low-latitude oceanic areas to mid- and high-latitude land areas. These high mountains act as a mechanical barrier to the air currents, and the north–south contrast across these mountains varied in magnitude with the glacial–interglacial cycles from 0.8 Ma on, at which time the glacial–interglacial climatic fluctuations reached their largest amplitude. The Asian monsoons thus control the atmospheric heat budget in the Northern Hemisphere, and changes in monsoonal intensity trigger global climate change.

See also

Carbon Cycle. El Niño Southern Oscillation (ENSO). Holocene Climate Variability. Oxygen Isotopes in the Ocean. Somali Current. Stable Carbon Isotope Variations in the Ocean. Upwelling Ecosystems.

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