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MONSOONS: PRE-QUATERNARY

Monsoon circulation has existed throughout geological history whenever the tropics were occupied by both land and sea. Pre-Quaternary monsoons, however, are poorly understood because paleo-monsoon studies have been heavily biased toward variations of the Quaternary monsoon on the orbital and suborbital time scales. Pre-Quaternary monsoon systems are often considered over a much longer time span, so they show more significant variations in responding to tectonically-induced geographic and topographic changes. Pre-Quaternary monsoons have so far only sporadically been mentioned in the literature for most of the geological periods, except for two better studied intervals: the Permian and Triassic where a "megamonsoon" developed on the megacontinent Pangaea, and the late Cenozoic, which led to the establishment of the modern monsoon system.

Megamonsoon of the megacontinent

As monsoons are caused by land-sea contrast in the heating rate, the ideal conditions for a monsoon system to develop exist when only one major continent and one complementary ocean exist on Earth. This was the real case around 250–200 Myr ago, during the late Permian and Triassic, when all continents assembled into two major landmasses, Laurasia and Gondwanaland, that joined near the equator to form the supercontinent Pangaea and the super-ocean Panthalassa (Figure M35a). The extensive distribution of evaporites and many biogeographic features indicate a maximum of continentality, leading to speculation about the association of monsoon-type seasonal rains with large landmasses at that time (Robinson, 1973). Parrish et al. (1982) used the basic principles of atmospheric and oceanic circulation to reconstruct global paleo-precipitation maps for seven time intervals of the Mesozoic and Cenozoic, and found patterns of a strong summer monsoon low over Laurasia and a winter monsoon high over Gondwanaland in the Triassic and reversed monsoon features for opposite seasons. According to these authors, the Triassic was distinguished by maximal aridity with precipitation on the supercontinent provided only by monsoons (Figure M35b). Kutzbach and Gallimore (1989) were the first to use numerical modeling to explore the "megamonsoon of the megacontinent." Applying a low-resolution general circulation model to the idealized Pangaea (Figure M35a), they found extreme continentality with a hot summer and cold winter, and large-scale summer and winter monsoon circulations (Figure M35c,d. At the same time, Crowley et al. (1989) used energy balance modeling (EBM) to study the late Permian climate. Both modeling results show an extremely wide annual range of temperature (50 °C) for hinterland and strong monsoon circulation over Pangaea.

The geological record of the "megamonsoon" was found from the upper Triassic of North America: the Newark and related basins in the east and the Colorado Plateau in the west (Figure M36a). Late Triassic lacustrine deposits from the Newark Basin, New Jersey, which were about 10° N in the monsoon-prevalent tropics at that time, display clear evidence of monsoon-driven seasonality and lake level fluctuations (Olsen, 1986). Part of the sequence consists of micro-laminated mudstones (varves) with 0.2–03 mm thin couplets of alternating light and dark layers, implying significant seasonal contrast (Figure M36b). Detailed studies including spectral analyses on the nearly 7,000 m long section reveal a full range of precession-related periods of lake level change: the 20-kyr precession cycles, and 100-kyr and 400-kyr eccentricity cycles which modulate the amplitude of precessional cyclicity (Figure M36c,d). All these cycles are characteristic of the tropical response to orbital forcing and support a monsoon-climate origin of lake level change, whereas the absence of obliquity cycles preclude the possibility of direct linkages to high-latitude climate systems (Olsen and Kent, 1996). Similar records of the Pangaean "megamonsoon" were also found in the Chinle Formation, Colorado Plateau, on the tropical western margin of the supercontinent (Figure M36a; Dubial et al., 1991). During the Pangaean interval, eolian, playa deposits and evaporates were widespread on the Colorado Plateau, but the Chinle formation represents an unusually wet episode with well-developed fluvial and lacustrine deposits and paleosol sequences, indicating abundant moisture brought about by enhanced monsoon circulation and strong seasonality.

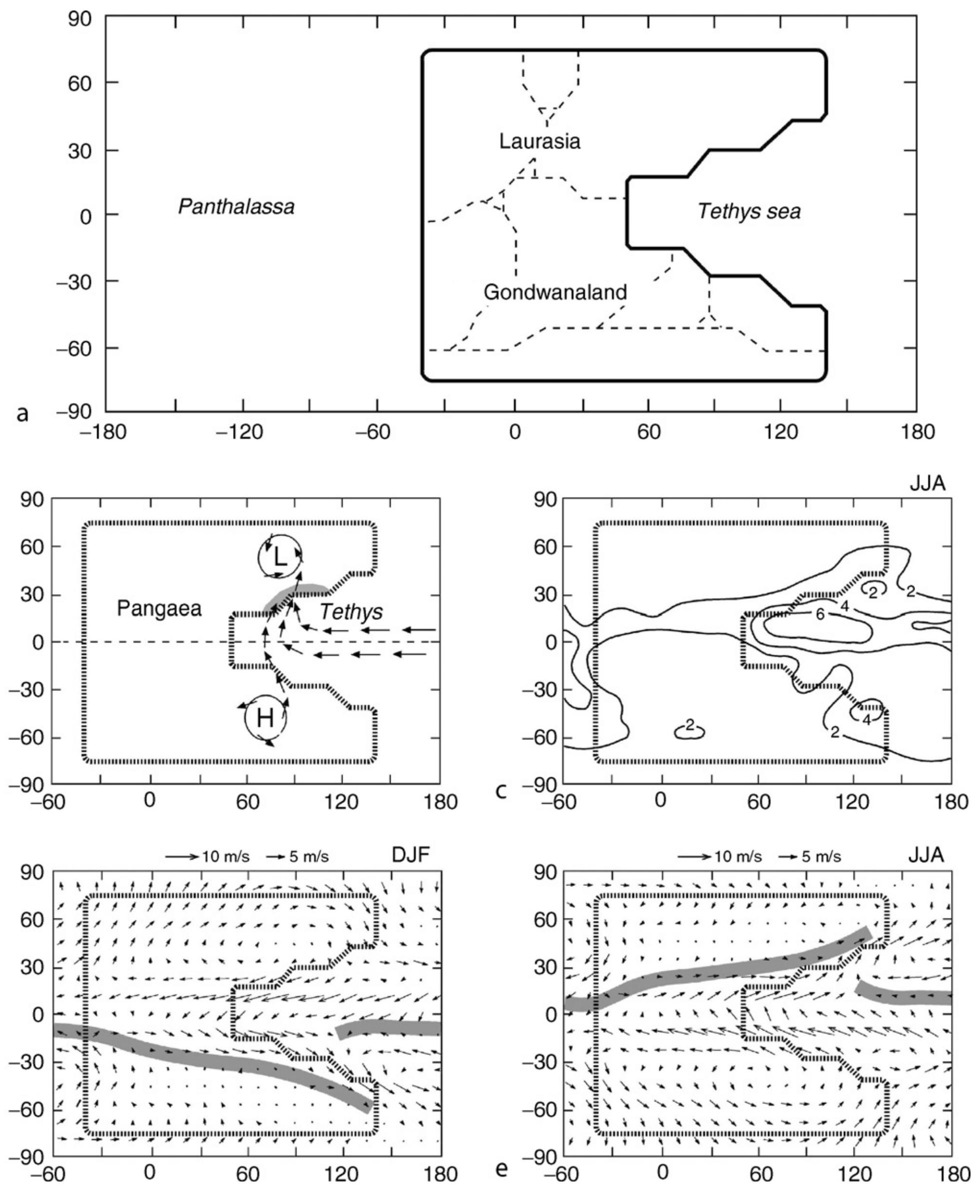

Figure M35 Megamonsoon of the Pangaea. (**a**) The idealized Pangaean continent. *Fine dashed lines* indicate the approximate outlines of modern landmasses (after Kutzbach and Gallimore, 1989). (**b**) Schematic diagram illustrating monsoonal circulation in northern summer. *Arrows* show surface winds, stippling indicates heavy seasonal rains (modified from Parrish and Peterson, 1988). (**c**) Modeled precipitation rate (mm d^{-1}) on Pangaea for summer. (**d**), (**e**) Modeled surface winds on Pangaea for winter (**d**) and summer (**e**), note the seasonal reversal of the wind direction. The *gray bar* shows the poleward limit of summer monsoon over land and the Intertropical Convergence Zone over ocean (modified from Kutzbach and Gallimore, 1989).

Establishment of the modern monsoon system

The modern Asian-Australian and African monsoons cover most of the Eastern Hemisphere, and fundamental questions in Cenozoic paleoclimatology ask when the modern monsoon system was established and how it has evolved since then. Three tectonic factors have been proposed to exert a control over the evolution of Asian monsoon circulation: plateau uplift, sea-land distribution, and closing of oceanic gateways. Continuous records of the monsoon history provided by Deep Sea Drilling Project/Ocean Drilling Program (DSDP/ODP) cruises to the Arabian, Mediterranean and South China Seas, as well as from the Loess plateau in central China, have been used to verify the various tectonic hypotheses (Sun and Wang, 2005).

Tectonic forcing and numerical modeling

1. **Plateau uplift.** GCM experiments on the modern land-sea distribution indicate that strong monsoons can be induced by solar forcing only when the elevation of Tibet-Himalaya has reached at least half that of today (Prell and Kutzbach, 1992). A number

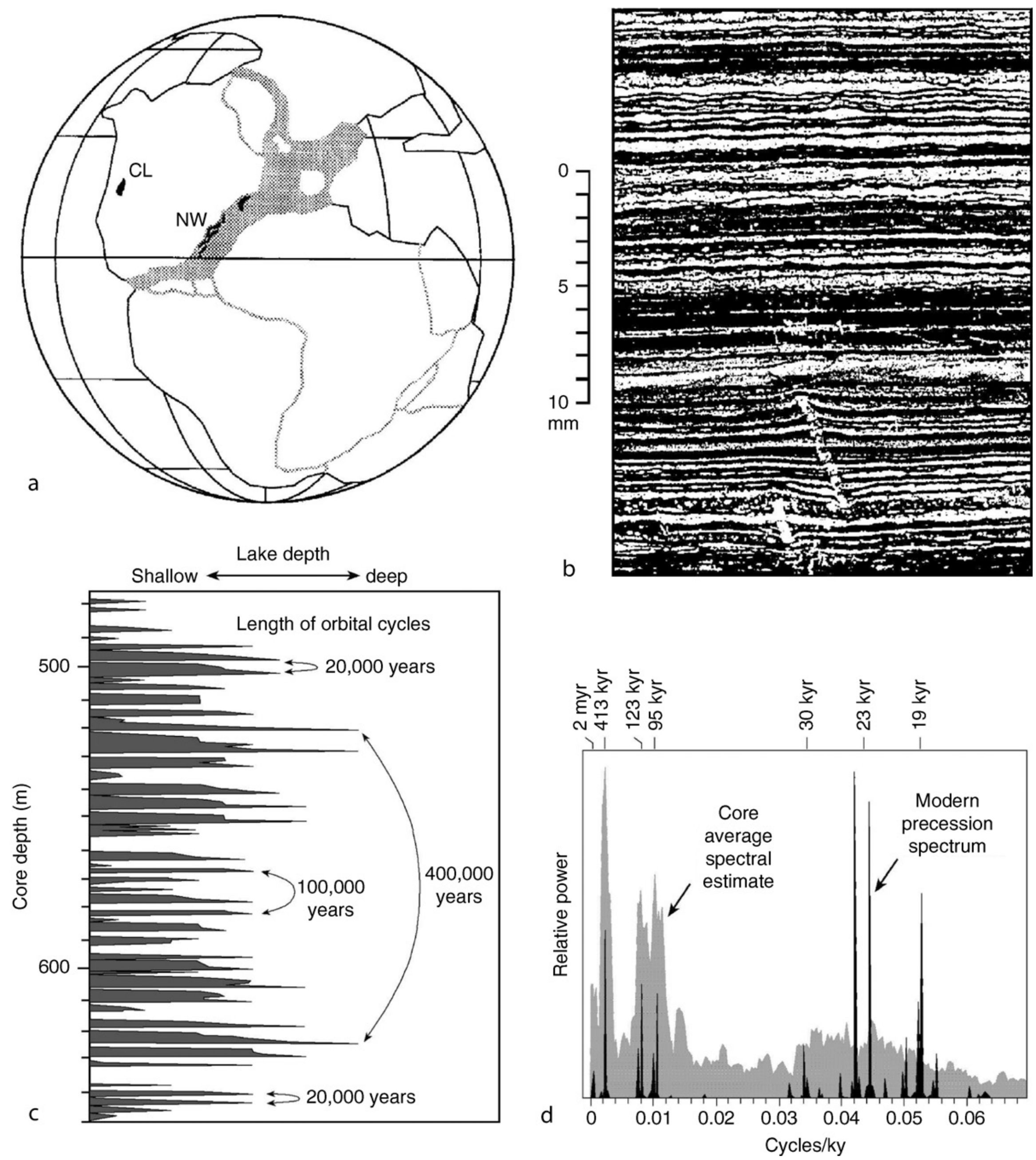

Figure M36 Late Triassic monsoon records from North America. (**a**) Locations of the Colorado Plateau with the Chinle Formation (*CL*) and, to the east, a chain of rifted basins containing the Newark Supergroup (NW). (**b**) Photograph of microlaminated mudstone showing organic-rich/carbonate-rich couplets as annual varves. (**c**) Lake-level fluctuations revealed in a section of the Newark lake sediments, showing 20-kyr, 100-kyr, and 400-kyr cycles. (**d**) Average spectral estimates of sediment cycles in the Newark Basin against the modern precession spectrum. (Modified from Olsen and Kent, 1996 and Ruddiman, 2001).

of studies in the late 1980s investigated the climatic consequences of uplift (e.g., Ruddiman et al., 1989) and found that uplift may have been responsible for both the global cooling and significant strengthening of the Asian monsoon system in the late Cenozoic. According to the prevalent hypothesis, uplift of the Tibetan Plateau intensified around 8 Ma and caused enhanced aridity over the Asian interior and the onset of the Indian and east Asian monsoons (Figure M37a, Prell and Kutzbach, 1997; An et al., 2001). However, this cognition is challenged by the new discovery of Miocene loess (Guo et al., 2002) and other evidence that indicates an older age (see below).

2. **Sea-land distribution.** The results of Atmospheric General Circulation Model (AGCM) simulation by Ramstein et al.

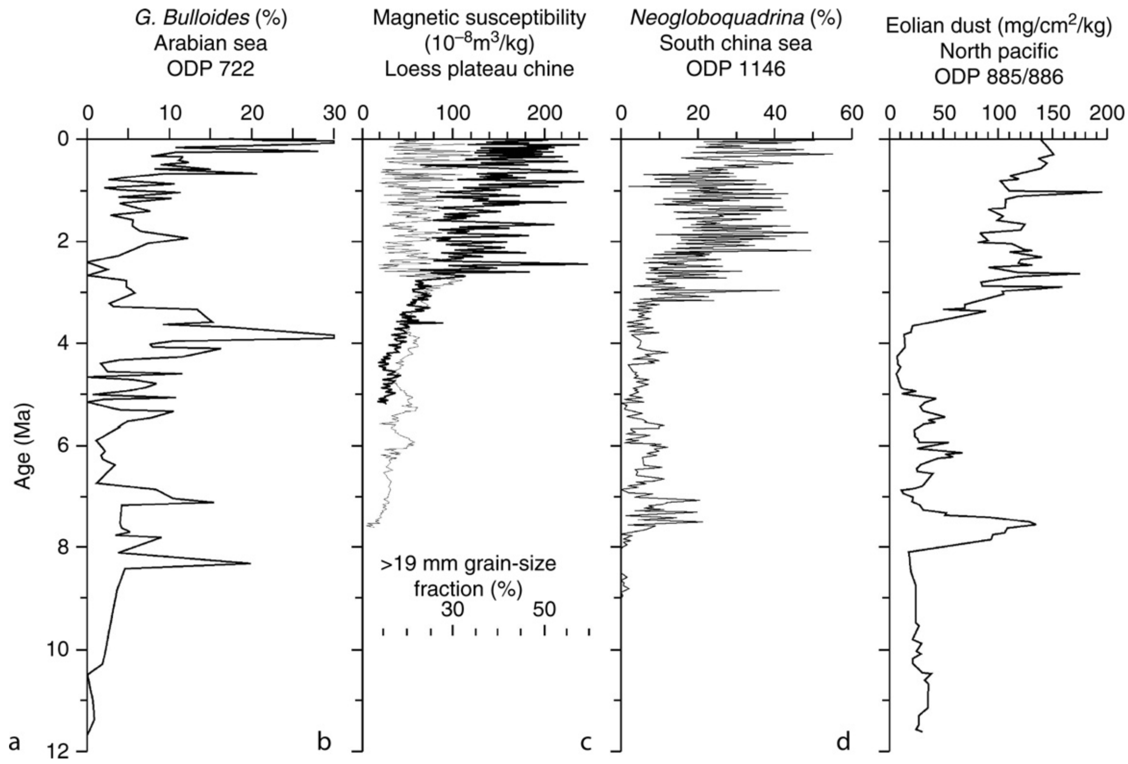

Figure M37 Records of Asian monsoon and aridity evolution over the past 12 Myr. (**a**) *Globigerina bulloides* % (>150 μm), ODP Site 722, Arabian Sea; (**b**) Magnetic susceptibility (*thin line*) and grain size fraction (*thick line*) from the Loess Plateau (An et al., 2001); (**c**) *Neogloboquadrina dutertrei* %, ODP Site 1146, South China Sea (Wang et al., 2003); (**d**) Dust flux (mg cm^{-2} kyr^{-1}), ODP sites 885/886, north Pacific (Rea et al., 1998).

(1997) indicate that the Paratethys, an epicontinental sea stretching over Eurasia 30 Ma ago, had progressively receded during the Miocene, resulting in major continentalization of the Asian interior and enhancement of monsoon circulation. They consider the retreat of the Paratethys Sea as important as the uplift of the Himalayan/Tibetan Plateau for development of the Asian monsoon. As the shrinkage of the Paratethys Sea occurred during the Oligocene-late Miocene, its effects on the monsoon may have lasted from 30 to 10 Ma, significantly earlier than the 8-Ma date implied by the uplift hypothesis.

3. **Oceanic gateways**. An oceanic circulation model reveals that the "closure" of the Indonesian seaway 3–4 Ma ago could be responsible for east African aridification (Cane and Molnar, 2001). The northward drift of the Australian Plate may have switched the source of the Indonesian Throughflow current from the warm South Pacific to the relatively cold North Pacific waters. This would have decreased Sea Surface Temperatures (SSTs) in the Indian Ocean and would have subsequently reduced precipitation over east Africa, as well as the overall strength of the Indian summer monsoon as recorded in marine deposits.

All of these three factors are believed to be significant in the development of the modern monsoon, but their relative roles remain unclear. To single out the role played by each of the factors, many more long-term sequences and better constraints on the timing of the tectonic and climate events are needed.

Geological records

Studies on the long-term evolution of the Asian monsoon started with ODP Leg 117 to the Arabian Sea in 1987. A sudden increase in the cool-water planktonic foraminifer *Globigerina bulloides* in sediment cores of Leg 117 around 8.5 Ma ago was considered by Kroon et al. (1991) as indicating the onset of monsoon-related upwelling (Figure M37a). This date is very close to the rapid ecological transition from C3-dominated to C4-dominated vegetation around 7.4–7.0 Ma, as revealed by the $\delta^{13}C$ data of pedogenic carbonates from northern Pakistan in the Himalayan foreland. These were interpreted as evidence for the origin or intensification of the Asian monsoon system (Quade et al., 1989). In addition, the dating of the extensive faults on the Tibetan Plateau suggests a significant uplift/extension period at about 8 Ma. On the basis of these findings and GCM simulations, Prell and Kutzbach (1992) hypothesized that uplift of the Tibetan Plateau to at least half of its present height at ~8 Ma caused the intensification of the Asian monsoon.

In the Chinese Loess Plateau, the base of the loess-paleosol sequences dated to about 2.6 Ma was previously taken as indicating the initiation of the East Asian monsoon (Liu and Ding, 1993). Later, Chinese scientists found that the Red Clay underlying the loess sequence was also of wind-blown origin and indicative of monsoon transport (Table M4), so the history of eolian deposits of the Loess Plateau should be extended to 7–8 Ma (Figure M37b; An et al., 2001). Since the uplift of the Tibetan Plateau can lead to enhanced aridity in the Asian interior and to intensification of the Asian monsoon system (Kutzbach et al., 1993), a nearly

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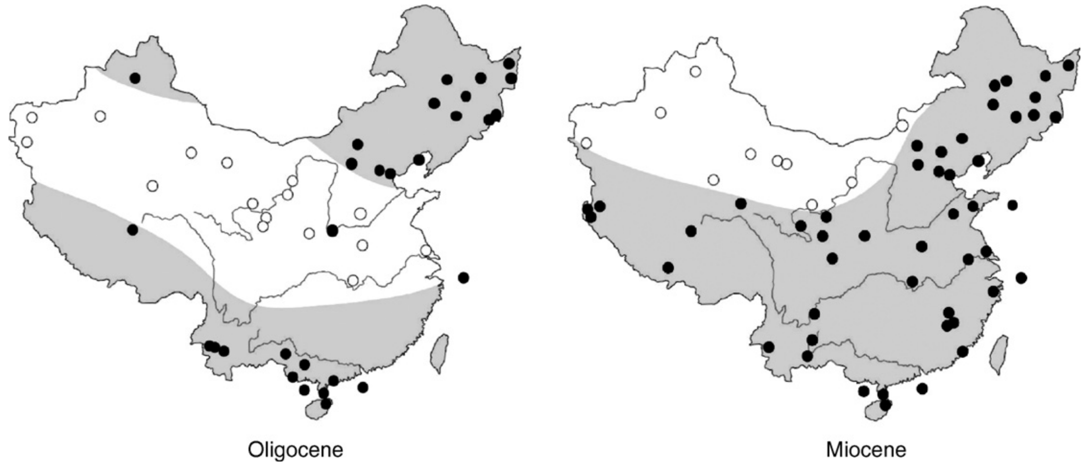

Figure M38 Distribution of arid climate zones in China based on paleobotanical and palynological data: (**a**) Oligocene; (**b**) Miocene. *Open dots* denote humid vegetation, *filled dots* denote arid vegetation. The Paleocene and Eocene patterns are similar to those of the Oligocene, while Pliocene and Pleistocene patterns are close to those of the Miocene. The drastic change between the Oligocene and Miocene implies the beginning of the modern East Asian monsoon system (Sun and Wang, 2005). Au2

Table M4 Development of the dust history in the Loess Plateau, China

Deposits	Age	Reference
Loess-paleosol sequence	0–2.6 Ma	Liu and Ding, 1993
Red clay	2.6–8 Ma	An et al., 2001
Qinan loess sequence	6.2–22 Ma	Guo et al., 2002

concurrent beginning of both the Indian Ocean upwelling and dust accumulation in central China about 8 Ma ago has been interpreted as marking the onset of the Indian and East Asian monsoons, which in turn implies a significant increase in the altitude of the Plateau (An et al., 2001). However, the recent discovery by Guo et al. (2002) of a Miocene loess sequence from Qinan, western Loess Plateau, has further extended the Chinese dust history. Like the Pleistocene loess, the Miocene loess evinces enhanced aridity in the dust source areas and energetic winter monsoon winds required for dust transport, whereas paleosols point to increased moisture supply by summer monsoon winds. A total of 231 interbedded loess-paleosol layers, representing a nearly continuous history of eolian dust accumulation from 22 to 6.2 Ma, indicates that large source areas of eolian dust and energetic winter monsoon winds existed since early Miocene, at least 14 Ma earlier than previously thought (Table M4).

Noticeable climate change from arid to humid climatic conditions in East China occurred as early as around the Oligocene/Miocene boundary. The synthesized data from oil exploration and stratigraphic studies indicate that a broad aridity belt stretched across China from west to east during the Paleogene, particularly in the Paleocene, before it contracted to Northwest China in the Neogene (Figure M37), suggesting a transition from a planetary to monsoonal system in atmospheric circulation over the region. This climate transition, now confirmed by abundant paleobotanical/palynological and lithostratigraphic data, may further imply that monsoonal moisture brought westward from the ocean to East China as a response to the reorganization of the climate system about 24 Ma ago was probably caused by an enhancement, if not the first establishment, of the East Asian summer monsoon (Sun and Wang, 2005). The loess-paleosol sequence at Qinan supports the Oligocene/Miocene climate transition. The existence of the Asian monsoon at about 16–14 Ma has been reported from northern Thailand, where middle Miocene mammalian faunas were found to have adopted to a monsoon-styled wet climate.

Sedimentological data from ODP Leg 116, Bay of Bengal also imply the intensification of uplift-induced monsoon in the early Miocene. Although the dramatic $\delta^{13}C$ increase of total organic carbon in Bengal Fan sediments at ca. 7 Ma supports the development of the monsoon in the Himalayan foreland at this time, the sediment accumulation records are in conflict with the 8 Ma uplift model. Accumulation rates at several DSDP/ODP Sites were high for the 17–7 Ma old Bengal Fan, but decreased from 7 to 1 Ma with the clay mineral assemblages indicating reduced physical erosion and strengthened chemical weathering (Derry and France-Lanord, 1997). No significant change in sediment accumulation around 8 Ma has been found at any ODP Leg 184 sites in the South China Sea (Wang et al., 2000). On the other hand, if using the planktonic foraminifer *Neogloboquadrina dutertrei* as an indicator of the East Asian monsoon and enhanced productivity in the South China Sea, its abundance peaks at 7.6 Ma and 3.2 Ma at Site 1146 on the northern slope correspond well to the Indian monsoon records (Figure M37c; Wang et al., 2003).

The dust record also indicates that the Asian monsoon system has a longer history and greater variability both in space and in time than previously thought. In the Miocene sequence of Qinan, two intervals are distinguished by higher dust accumulation: 15–13 Ma and 8–7 Ma (Guo et al., 2002). These might represent periods of enhanced aridity in the source areas, an interpretation supported by pollen data from Yumen, northeast of Tibet. Increased aridity over Asia around 8–7 Ma also explains a peak in dust accumulation rate in the North Pacific (Figure M37d; Rea et al., 1998).

Monsoon evolution in geological history

The number and geographic coverage of the monsoon records decrease with increasing age, resulting in relatively deficient knowledge of the pre-Quaternary monsoon history. Although it may be premature to discuss the evolution of the monsoon system through the entire geological history, the examples of the Pangaean and late Cenozoic times provide convincing evidence that tectonically-induced changes in sea-land distribution and in topography have played the primary role in controlling the monsoon system over the 10^6–10^7 year and longer timescales. Tracing back the entire Phanerozoic history, the monsoon system strengthened with increased size of continents and increased altitude of mountains. With the collapse of the megacontinent, for example, the "megamonsoon" circulation over Pangaea was subsequently replaced by a basically zonal circulation (Parrish et al., 1982). The late paleozoic American Appalachians (estimated average altitude of 4,500 m) and the European Variscan (2,000–3,000 m) in Pangaea might have played a role similar to the late Cenozoic Himalaya-Tibet in the intensification of the concomitant monsoon circulation (Fluteau et al., 2001).

The development of polar ice-sheets is another major control of the monsoon system. Clemens et al. (1996) found a nonstationarity in the phase of the summer monsoon system relative to a growing Northern Hemisphere ice volume over the past 3.5 Myr. During the initiation and the growth of the Northern Hemisphere ice sheets, the phase of strong monsoons moved away from the phase of maximum ice volume and systematically drifted in a similar pattern over the past 2.6 Myr. An intensified winter monsoon resulting from the growth of the boreal ice sheet was also reported from the Chinese loess records (Liu and Ding, 1993). Accordingly, the nature of the monsoon system in the ice-house vs. hot-house Earth must have been different, and the transition between hot- and ice-house regimes can be of paramount importance for reconstructing the monsoon history.

A trustworthy reconstruction of the monsoon history depends on the proxies adopted. Care is necessary to evaluate how the monsoon proxies that were developed for the Quaternary period can be applied to the earlier geological past. It is equally crucial to distinguish monsoon proxies from those driven by other factors. An example is the late Miocene development of C4 vegetation, exhibited by a δ^{13}C shift in pedogenic carbonates, which was considered by Quade et al., (1989) as a signal of the onset of the Indian monsoon when first found in Pakistan. Since many subsequent findings have occurred in various continents, this δ^{13}C shift has been re-interpreted as representing a large-scale vegetation change caused by decreased CO_2 concentration on the globe (Cerling et al., 1997).

Regardless of all the complexity, paleo-monsoons are increasingly important in pre-Quaternary studies. Climate variations throughout geological history have been driven not only by higher latitudes where ice-sheets develop but also by lower latitude factors, especially by the monsoons.

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Cross references

Atmospheric Evolution, Earth
Deep Sea Drilling Project (DSDP)
Loess Deposits
Monsoons, Quaternary
Mountain Uplift and Climate Change
Ocean Drilling Program (ODP)
Plate Tectonics and Climate Change
Precession, Climatic
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