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Blowing in the Monsoon Wind

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ABSTRACT. From *Maswin* (Arabic), to *Monção* (Portuguese), to *Moesson* (Dutch), to *Monsoon* (English), the etymology of the word is not entirely clear, nor is its definition precise, although these different terms all refer to seasonal changes in wind and rainfall, depending on where they occur. However, it is clear that monsoonal climates are characterized by strong seasonality in wind and rainfall patterns, typically with onshore winds and increased rainfall during summer and offshore winds and reduced rainfall during winter. The Northern Hemisphere monsoons are one of the most prominent examples of Earth system interactions in which the solid Earth influences the circulation of the atmosphere and ocean, consequently forcing aspects of both regional and global climate. The monsoons also represent a climate phenomenon that has large direct and indirect societal impact. In this paper we review the contribution of scientific ocean drilling to our understanding of Earth's current monsoons as well as those through geological history, back to tens of millions of years ago.

Windsock on *JOIDES Resolution* at sunset during International Ocean Discovery Program Expedition 353, Indian Ocean Monsoon. *Photo credit: Edmund Hathorne, IODP JRSO*

INTRODUCTION

Historically, monsoonal circulation has been widely studied by both the climatology and the paleoclimate research communities. With increasing recognition of climate change, so has its social relevance grown. Until the nineteenth century, an understanding of monsoon winds was crucial for navigation. Later, when steamboats replaced sailboats, monsoon precipitation became a major social concern because of its association with floods, droughts, and food production. Today, monsoons are recognized as being central to the global hydrological cycle, but they remain insufficiently understood.

Monsoons have likely been prominent features of Earth's climate system throughout much of geologic time, and their influence as global climate changes is as critical as that of the ice sheets, sea ice, and sea level. Although monsoon precipitation accounts for only one-third of the total modern global rainfall, it is the most mutable component in the global hydrological cycle. Together with the El Niño-Southern Oscillation (ENSO) and trade winds, the global monsoon is a major low-latitude component of the global climate system, and thus its study on timescales ranging from interannual to geological enhance our understanding of key factors that control the hydrological cycle. Transitions between water's physical phases pervade and drive the entire climate system, but in the past, the paleoclimate community focused on solid/liquid (i.e., ice/water) phase transitions, while liquid/gaseous transitions went almost unexplored until very recently, largely due to difficulties in research approaches and insufficient proxies (P. Wang et al., 2017).

Although achieving a better understanding of ocean-atmosphere processes has been a scientific ocean drilling goal since the beginning of the Deep Sea Drilling Project (1968–1983), the focus on monsoons did not emerge until the early 1980s. At that time, analysis of sediments recovered from the ocean showed that deposits reflecting upwelling-enhanced productivity and eolian transport were linked to monsoon winds and the westerlies from Asia to the North Pacific, respectively (see Rea, 1994, for a review). The first expedition designed specifically to reconstruct Asian monsoon history was Ocean Drilling Program (ODP) Leg 117 to the northeast Arabian Sea in 1987 (Prell et al., 1989). ODP Leg 184 to the South China Sea followed in 1999, also aimed at monsoon reconstruction. Both of these drilling legs resulted in new insights into the history of Asian monsoon climates from tectonic to orbital timescales, showcasing the application and effectiveness of using proxies to resolve monsoon-related processes (e.g., Kroon et al., 1991).

In the twenty-first century, monsoons have received greater attention from both the paleo- and modern climatology communities. In the modern world, monsoonal circulation exists, to varying degrees, on all continents except Antarctica. The Asian monsoon is the most active among all the regional systems and includes three different subsystems: the Indian tropical, the Southeast Asian tropical, and the Northeast Asian subtropical (Figure 1). The Northeast Asian monsoon reaches the highest latitude (45°N) and is the most complicated of the subsystems.

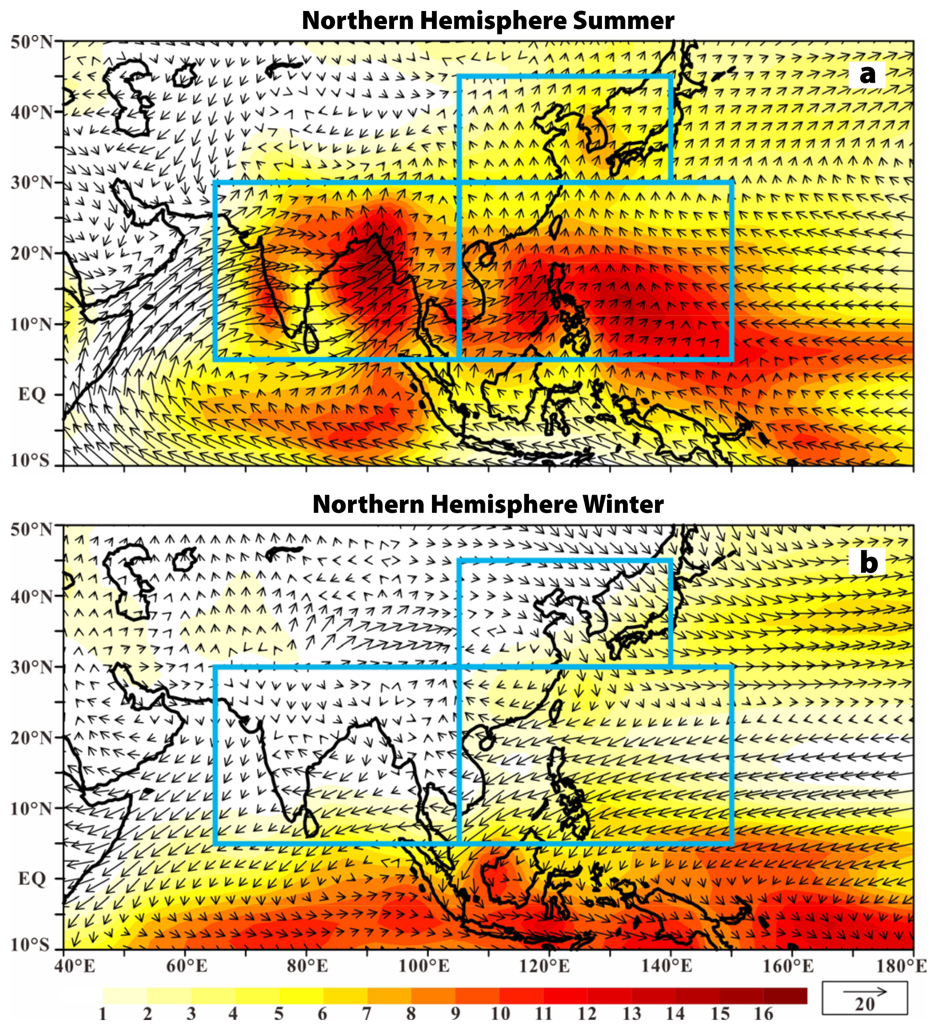


FIGURE 1. Climatological mean precipitation rates (shading in millimeters per day) and lower-level wind vector (arrows) in the Asian monsoon region. (a) July–August. (b) January–February. The three boxes define the major summer precipitation areas of the Indian tropical, Southeast Asian tropical, and the Northeast Asian subtropical monsoons. *Modified from B. Wang et al. (2003)*

Six Integrated Ocean Drilling Program and International Ocean Discovery Program (IODP) expeditions were completed between 2013 and 2017 to explore the Cenozoic history of all three monsoon systems (Figure 2), and to date, a total of nine ODP/IODP cruises have been implemented to specifically address Asian monsoon variability and impacts (Table 1). The deep-sea sediment sequences recovered from these expeditions provide invaluable climate archives for studying the evolution of the Asian monsoon since the Oligocene.

Monsoon Proxies

Wind and rainfall patterns vary strongly across the monsoon regions, imparting different chemical, physical, biological, and isotopic signals to the underlying sediments. Thus, a variety of ocean sediment proxies are used in different regions, depending on which aspect of the monsoon is being reconstructed. For example, the dominant monsoonal signals in the Arabian Sea region derive from the low level Findlater jet and eolian transport of lithogenic materials from the surrounding deserts. Here, the Findlater jet develops during the summer season, flowing from the southwest along the Somali coast (Figure 1a), driving Ekman-induced upwelling along the coastline, while lithogenic dust is transported to the Arabian Sea. In this case, lithogenic grain size changes in the ocean sediments, and planktonic foraminifera species associated with upwelling environments (e.g., *Globigerina bulloides*; Figure 3d) can be used as proxies for changes in summer monsoon wind strength. In scientific ocean drilling cores, these monsoon processes result in alternating light-dark bands (Figure 3a), indicating dilution of light-colored biogenic carbonates (summer monsoon productivity) by dark-colored terrestrial dust input, driven by glacial-interglacial changes in vegetation cover and increased deflation potential (i.e., the removal of fine sediments and organic materials by strong winds). Changes in oceanic upwelling strength also drive changes in underlying oxygen minimum zone (OMZ) denitrification that can be reconstructed using nitrogen isotopes, with increased upwelling causing an increase in $\delta^{15}N$ in bulk organics in northern Arabian Sea sediment cores. The extent to which multiple independent proxies converge on similar results provides a measure of confidence, given that each proxy may be biased in some way by processes unrelated to monsoon variability (e.g., diagenesis, dissolution, physical disturbance).

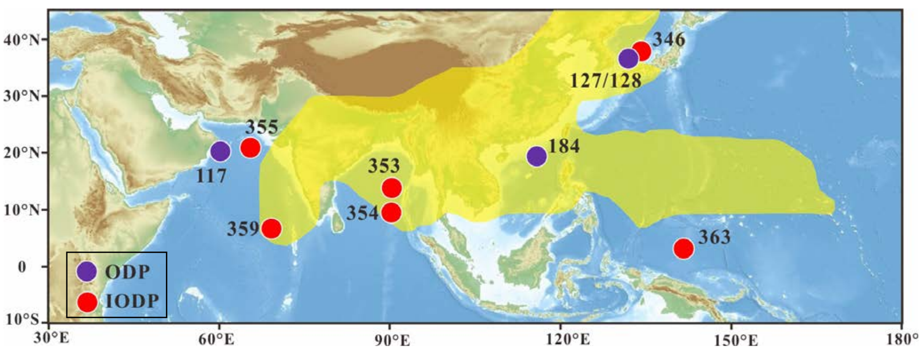


FIGURE 2. Scientific ocean drilling expeditions that have addressed the Asian monsoon. Purple dots indicate Ocean Drilling Program (ODP) legs, red dots Integrated Ocean Drilling Program and International Ocean Discovery Program (IODP) expeditions. Yellow coloring denotes the modern Asian monsoon region.

TABLE 1. IODP and ODP expeditions addressing the Asian monsoon.

Expedition	Drill Area	Age*	Year	Drill Sites	References
IODP 363	West Pacific Warm Pool	Miocene/Oligocene	2016	U1482–1490	Rosenthal et al., 2018
IODP 359	Maldives	Miocene/Oligocene	2015	U1465–1472	Betzler et al., 2017
IODP 355	Arabian Sea	17.7 million years	2015	U1456–1457	Pandey et al., 2016
IODP 354	Bengal Fan	Late Miocene	2015	U1449–1455	France-Lanord et al., 2016
IODP 353	Bay of Bengal	Cretaceous	2014/15	U1443–1448	Clemens et al., 2016
IODP 346	Sea of Japan, East China Sea	12 million years	2013	U1422–1430	Tada et al., 2015
ODP 184	South China Sea	33 million years	1999	1143–1148	P. Wang et al., 2000
ODP 127/128	Sea of Japan	20 million years	1989	744–749	Pisciotto et al., 1992
ODP 117	Oman Margin	17 million years	1987	720–731	Prell et al., 1989

* "Age" indicates the oldest age of recovered sediments

In contrast to the Arabian Sea record, the primary monsoon signal in ocean sediments in the Bay of Bengal region derives from strong summer rainfall (Figure 1a). Here, the monsoon signal can be teased out in scientific ocean drilling cores by observing changes in lithogenic influx and seawater $\delta^{18}O$ as obtained from the $\delta^{18}O$ mass spectrometry analyses of the planktonic foraminifer *Globigerina ruber* (Figure 3c) that in turn is coupled with temperature reconstructions, both of which vary as a function of rainfall and runoff. In addition, the δD (hydrogen isotopic) composition of terrestrial leaf wax (Figure 3b) can be used to monitor the isotopic composition of monsoon rainfall on land, which is useful in the South China Sea, East China Sea, and Japan Sea where rivers enter these marginal basins and dilute ocean waters. Monsoon proxies from terrestrial archives are abundant as well, but the correlation between various proxies remains a subject of debate and is outside the scope of this work.

TECTONICS-CLIMATE LINKAGE

Tectonic-Climate Links and the Uplift-Monsoon Hypothesis

Theoretically, it is expected that the seasonal reversal of surface winds driven by basic atmospheric processes should have produced monsoonal climates in the lower latitudes throughout geological history. Yet, the onset and cause of the modern pattern of regional monsoons remains a fundamental outstanding question of considerable interest. Early research suggested that Himalayan-Tibetan plateau uplift was responsible for monsoon evolution in Asia/India, leading to the uplift-monsoon hypothesis (Prell and Kutzbach, 1992).

Today, three tectonic factors have been proposed as exercising control over the evolution of the Asian monsoon: plateau uplift, changing sea-land distributions, and the opening and closing of oceanic gateways. In the Himalaya-Tibet region, plateau uplift alone may involve various mechanisms that affect monsoon circulation, including thermal forcing at the plateau surface, mechanical barriers related to regional orography, and "candle heating" in the middle troposphere (see P. Wang et al., 2017, for a review). General circulation models (Figure 4a) predict the inception of strong monsoons (similar to the modern-day Asian monsoon) when the uplift of Himalaya-Tibet is at least half that of the present (Prell and Kutzbach, 1992). Increases in the presence of the monsoon upwelling indicator, *Globigerina bulloides*, at ODP Arabian Sea Site 722 suggest the onset of strong monsoonal conditions began ~8 million years ago (Figure 4b; Kroon et al., 1991), coincident with a major phase of uplift of the Himalayan mountain range 10.9–7.5 million years ago (Amano and Taira, 1992). This uplift-monsoon hypothesis was supported by terrestrial records of enhanced wet/dry seasonality, including accelerated loess deposition in China (Ding et al.,

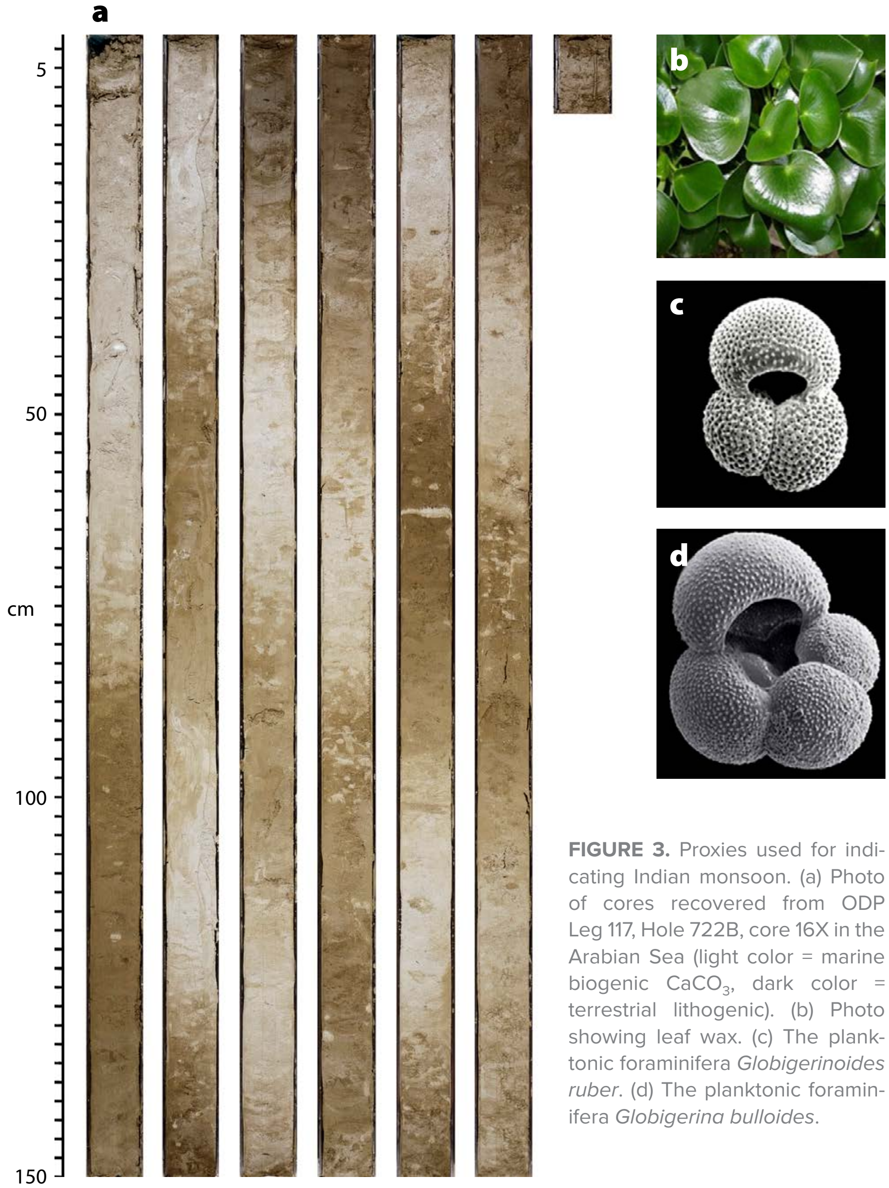


FIGURE 3. Proxies used for indicating Indian monsoon. (a) Photo of cores recovered from ODP Leg 117, Hole 722B, core 16X in the Arabian Sea (light color = marine biogenic $CaCO_3$, dark color = terrestrial lithogenic). (b) Photo showing leaf wax. (c) The planktonic foraminifera *Globigerinoides ruber*. (d) The planktonic foraminifera *Globigerina bulloides*.

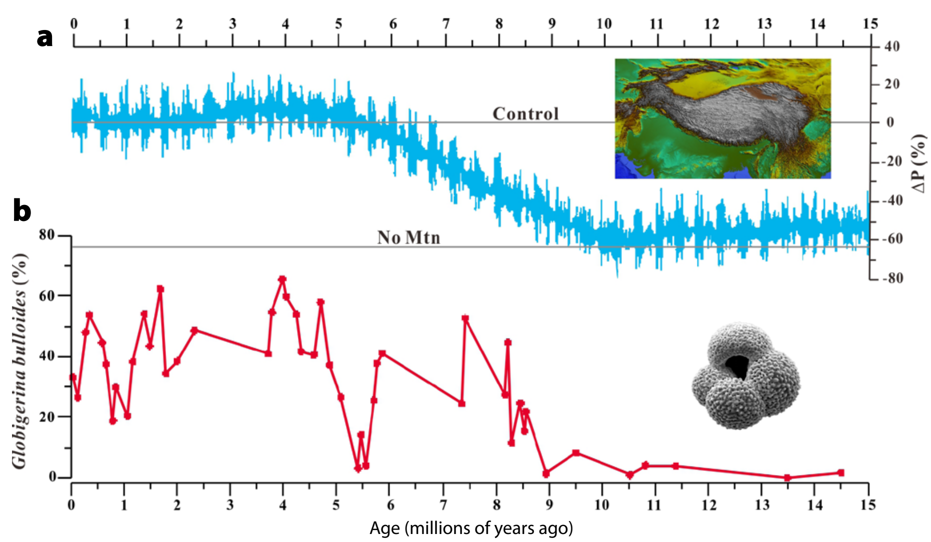


FIGURE 4. Tibetan uplift and development of the Indian monsoon. (a) Model of the uplift showing percentage changes in monsoon precipitation (%ΔP, mm d^{-1}). (b) Time series of upwelling indicator species of planktic foraminifer *Globigerina bulloides* from ODP Site 722. *Modified from Prell and Kutzbach (1992)*

1998) and an ecological transition from C_3- to C_4-dominated vegetation (when plants started to fix CO_2 twice in their cell structures) in Northern Pakistan around that time (Quade et al., 1989).

However, not all long-term changes to the Asian monsoon have resulted from direct tectonic forcing. An example is intensification of Asian aridity and monsoon at about 3 million years ago, as convincingly documented both on land and in the ocean. Almost all data suggest that this event was not related to uplift but to changes in global climate resulting from the permanent glaciation of Greenland (P. Wang et al., 2005).

East Asian Monsoon

Continued investigation of the causal relationship between uplift and the strength of the Asian monsoons revealed a much more complicated and dynamic Earth system, particularly in eastern Asia. The discovery of older loess dating to the Early Miocene (Guo et al., 2002) and the reorganization of the climate system in China around the transition from the Oligocene to the Miocene provides evidence for enhancement or perhaps establishment of the East Asian monsoon around 23 million years ago (Sun and Wang, 2005). A 33-million-year sequence of hemipelagic sediments recovered from the South China Sea at ODP Site 1148 provided an ideal record for investigating the timing of the onset of Asian monsoons. For example, the isotopic composition of black carbon ($\delta^{13}C_{BC}$) and chemical alteration indices from Site 1148 suggest major changes in seasonal precipitation since the early Miocene (Figure 5a, Wei et al., 2006), significantly predating the original ~8 million year monsoon initiation age derived from earlier studies. The strong $\delta^{13}C_{BC}$ fluctuations were ascribed by Jia et al. (2003) to the initiation of the modern East Asian monsoon, in agreement with terrestrial records. These authors also attributed the general trend of $\delta^{13}C_{BC}$ toward much more positive values in the early Pleistocene to a drying in East Asia, and maybe a temporary ceasing or de-intensifying of the monsoon, supported also by geochemical indices, such as the chemical index of alteration (CIA; Figure 5b). Similar patterns in Rb/Sr and CIA at South China Sea ODP Site 1146 (Figure 5c,d; Wan et al., 2010) support the regional nature of the drying trend in East Asia.

Both the South China Sea records and the North Asian terrestrial data indicate a strengthening of the East Asian monsoon, marked by the transition from zonal to monsoonal climate patterns around 23 million years ago. Clift et al. (2014) proposed that after the strengthening of the East Asian monsoon at ~23 million years ago, another extended period of monsoon maximum in East Asia occurred between 18 and 10 million years ago, but weakened around 8–7 million years ago, showing an opposite trend to the Arabian Sea wind strength record that informs our understanding of the Indian monsoon (Figure 4b). It remains unclear, however, whether the development of East Asian and Indian monsoons was synchronous at the tectonic timescale, and whether the two monsoon subsystems shared a common tectonic forcing. Another factor that must be reconciled is whether the drying trend in the Neogene was related to global-scale cooling. The major obstacle to resolving these issues is the absence of long-term records of the Indian monsoon; hopefully, ongoing investigations of the Eocene-Pleistocene sequences recovered from IODP Expeditions 353, 354, 355, and 359 to the Bengal Fan will shed light on this issue.

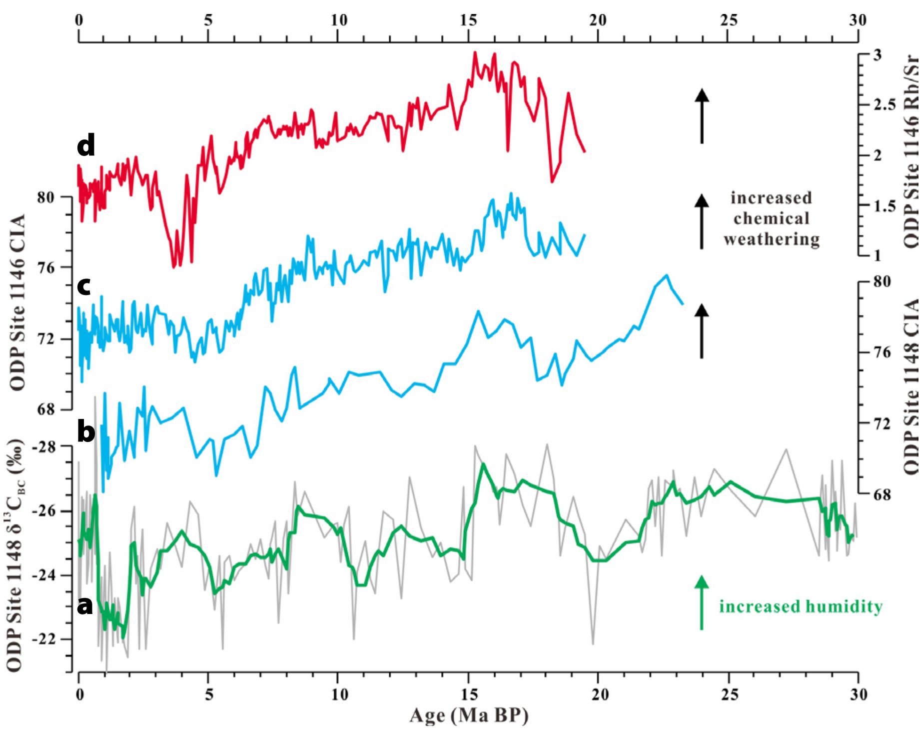


FIGURE 5. Late Cenozoic climate records from the South China Sea. ODP Site 1148: (a) Isotopic composition of black carbon over the past 30 million years (Jia et al., 2003). (b) Chemical index of alteration (CIA) over the past 25 million years (Wei et al., 2006). ODP Site 1146: (c) Rb/Sr ratio and (d) CIA over the past 20 million years (Wan et al., 2010).

Indian Monsoon

While relatively long and continuous sediment records exist to investigate the East Asian monsoon, early studies of Indian monsoon history were hindered by the lack of long sediment sequences. Among the recent IODP expeditions addressing Indian monsoon history, IODP Expedition 359 to the Maldives recovered a record back to 25 million years ago (Betzler et al., 2017). The cores display an abrupt change in sedimentation pattern, also marked by a large decrease in manganese concentration at 12.9 million years ago, likely indicating the onset of the Indian monsoon (Betzler et al., 2018). Here, wind-driven upwelling during the summer monsoon generates an OMZ in the Arabian Sea, whereby the amount of manganese buried with the sediment varies with changes in OMZ intensity. The Mn/Ca ratio from analysis of interstitial waters can therefore be used as a proxy to indicate the summer Indian monsoon (Figure 6b; Betzler et al., 2016, 2018). In contrast, a discontinuous ~10.2-million-year record of denitrification in the eastern Arabian Sea within the OMZ recovered from IODP Expedition 355 indicates a persistently weakened Indian monsoon from ~10.2 to 3.1 million years ago (Figure 6a; Tripathi et al., 2017). This monsoonal weakening trend from the eastern Arabian Sea contrasts with the maximum monsoon between 10.2 and 3.8 million years ago, as interpreted from the Maldives record (Figure 6b; Betzler et al., 2018), likely highlighting the importance of regional variability throughout the larger Asian monsoon system.

Although it is premature to draw conclusions about the impact of tectonics on overall Asian monsoon evolution, some long-term records from recent expeditions may shed light on this crucial issue. IODP Expedition 354 to the Bengal Fan, for example, drilled seven sites and recovered a comprehensive record of Himalayan erosion over the Neogene and Quaternary (France-Lanord et al., 2016). Major and trace element geochemistry show relatively stable compositions throughout the period, and the low weathering intensity suggests that a monsoon-style erosion regime, with rapid sediment transfer through the floodplain, was established since at least the Early Miocene (France-Lanord et al., 2017).

ORBITAL FORCING AND THE MONSOON

Interpreting Orbital-Scale Records

Compared to tectonic timescales (millions of years), our knowledge of the large-scale Asian monsoon evolution at orbital timescales (less than tens to hundreds of thousands of years) is more complete. The study of orbital-scale climate change is unique in that the signal-to-noise ratio is large and the insolation forcing (i.e., changes in the amount of sunlight warming a given area on Earth) is well known over the past 20 million years (see Littler et al., 2019, in this issue). For the late Pleistocene, this knowledge has significantly improved the resolution at which we understand the distribution of greenhouse gases (carbon dioxide and methane) and terrestrial ice volume (Loulergue et al., 2008; Petit et al., 1999; Lisiecki and Raymo, 2005) and their effects on global climate.

Changes in insolation derive from three orbital parameters: (1) eccentricity (e) that describes the deviation of Earth's orbit from circularity, (2) obliquity (ε) or tilt of Earth's rotation axis, and (3) the precession index (esinω), which is a function of eccentricity and describes the orientation of Earth's rotation axis relative to the fixed stars, where ω is the longitude of perihelion measured relative to the moving vernal equinox (Berger, 1978). Therefore, it should be possible to assess the underlying mechanisms driving monsoonal climate change at the orbital timescale. One approach to interpreting orbital-scale monsoon reconstructions is to assess the coherence and phase of the proxy records relative to the external (insolation) and internal (e.g., greenhouse gas, terrestrial ice volume) climate forcing mechanisms at each of the primary orbital periods: eccentricity (~100,0000 years), obliquity (41,000 years), and precession (23,000 years). Given statistically significant coherence within discrete orbital periods, differences in phase offer measures of relative climate sensitivity and the underlying physics driving monsoonal climate change.

Here, we examine the precession-band response, as insolation is dominated by precession-band variance in monsoonal regions, and we use the phase wheel as a convenient means of depicting the timing of the monsoon response relative to known forcings (Clemens et al., 1991; Figure 7a). The maximum external forcing in terms of precession occurs during the June 21 perihelion. In the phase wheel, this is set at 0° (top) and represents the timing of the strongest Northern Hemisphere summer monsoon insolation, maximum sensible heating of the Indo-Asian landmass. If monsoon circulation responded only to this external insolation forcing, all monsoon proxy responses would

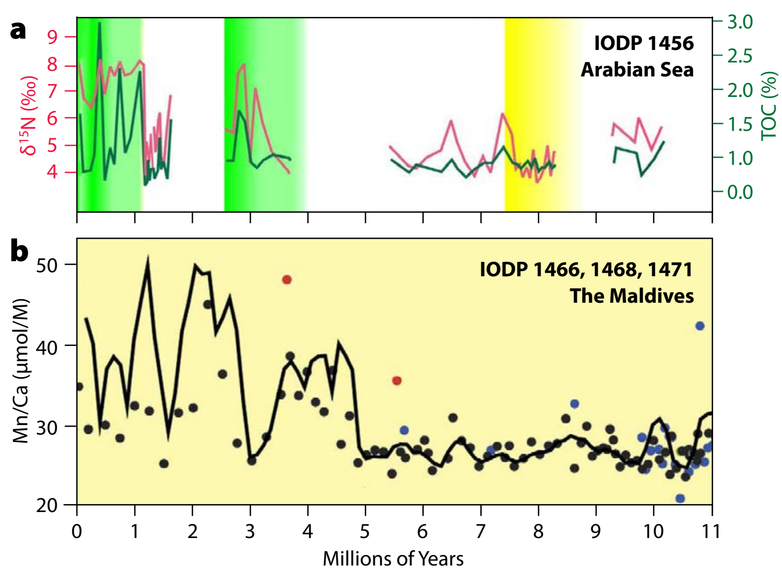


FIGURE 6. Comparison between two ~10-million-year IODP records. (a) $\delta^{15}N$ and total organic carbon (TOC) at IODP Site 1456, Eastern Arabian Sea (Tripathi et al., 2017). (b) Mn/Ca ratio at IODP Sites 1466, 1468, and 1471, Maldives (Betzler et al., 2018).

plot near 0°, coherent and in phase with the maximum sensible heat forcing. In Figure 7, the precession-band timing of *potential* monsoon forcing mechanisms are depicted with red dots and associated labels, including insolation through Northern Hemisphere sensible heating, the greenhouse gases CH_4 and CO_2, minimal terrestrial ice volume, and latent heat export from the Southern Hemisphere subtropical Indian Ocean (Figure 7b).

The precession timing of the monsoon proxy reconstructions are shown in blue in Figure 7, illustrating selected Late Pleistocene results from scientific ocean drilling sites in the northwest Arabian Sea (Clemens et al., 1991, 2003), Bay of Bengal (Bolton et al., 2013; Gebregiorgis et al., 2018), northern South China Sea (Thomas et al., 2014), and northeastern East China Sea (Clemens et al., 2018). To a first approximation, proxies from the South China Sea and East China Sea derived from ODP Leg 184 and IODP Expedition 346 indicate strengthened monsoonal circulation between the timing of maximum Northern Hemisphere summer insolation, the internal CH_4 and CO_2 greenhouse gas forcings, and the climatic boundary conditions associated with the growth and decay of high-latitude ice sheets (Figure 7b). In contrast, proxy records from the northwest Arabian Sea and the Bay of Bengal derived from ODP Legs 117 and 121 and IODP Expedition 353 reach their maxima between the minimum ice volumes and the maximum latent heat exports from the southern subtropical Indian Ocean, consistent with the cross-equatorial flow path of modern winds and moisture (Figure 1).

From this synthesis, a picture is slowly emerging in which (1) the timing of strengthened circulation in the East Asian monsoonal system appears sensitive to direct Northern Hemisphere summer insolation forcing and changes in greenhouse gases/ice volume that is (2) decoupled from the Indian monsoonal system, which appears more sensitive to changes in greenhouse gases/ice volume as well as the import of latent heat from the southern subtropical Indian Ocean. This decoupling is consistent with the apparent asynchronous intensification and weakening of the East Asian and Indian monsoons at longer timescales as evidenced in many ODP and IODP sediment cores.

Neogene Monsoon and Eccentricity Cycles

The above discussion focused on precession-band variance. However, the precession amplitude is (strongly) modulated by Earth's orbital eccentricity in long paleoclimate sequences that span many eccentricity-driven modulation periods at 95,000, 124,000, and 404,000 years. There is a clear advantage in using scientific ocean drilling for such studies, because the program's global-class drilling platforms are capable of recovering long sediment archives that span the entire Cenozoic and into the Cretaceous, and across large ocean expanses. The middle Miocene records from ODP Site 1146, northern South China Sea, and IODP Site 1237, Southeast Pacific, for example, show high coherence between the benthic $\delta^{13}C$ and the long (404,000 year) and short (95,000 and 124,000 year) eccentricity cycles (Figure 8). The "Monterey" carbon-isotope excursion (16.9–13.5 million years ago) consists of nine 400,000-year cycles, implying carbon reservoir changes linked to eccentricity forcing, possibly mediated through enhanced biological productivity and increased organic carbon burial in continental margin

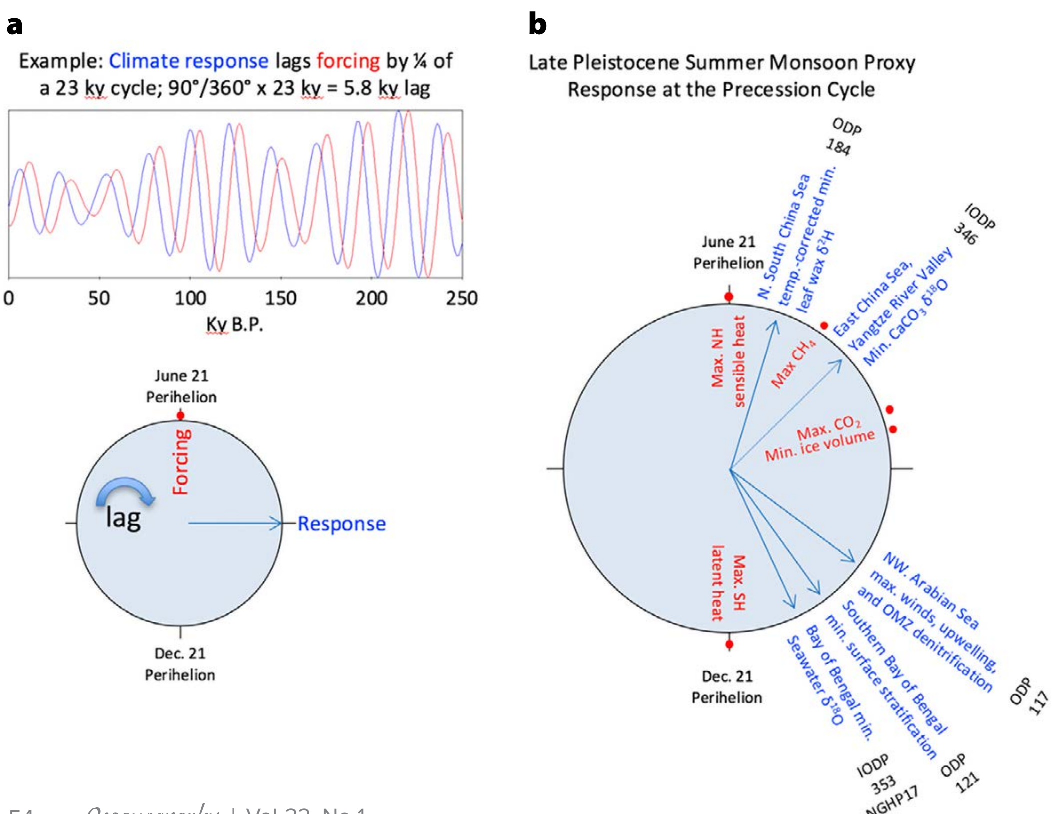
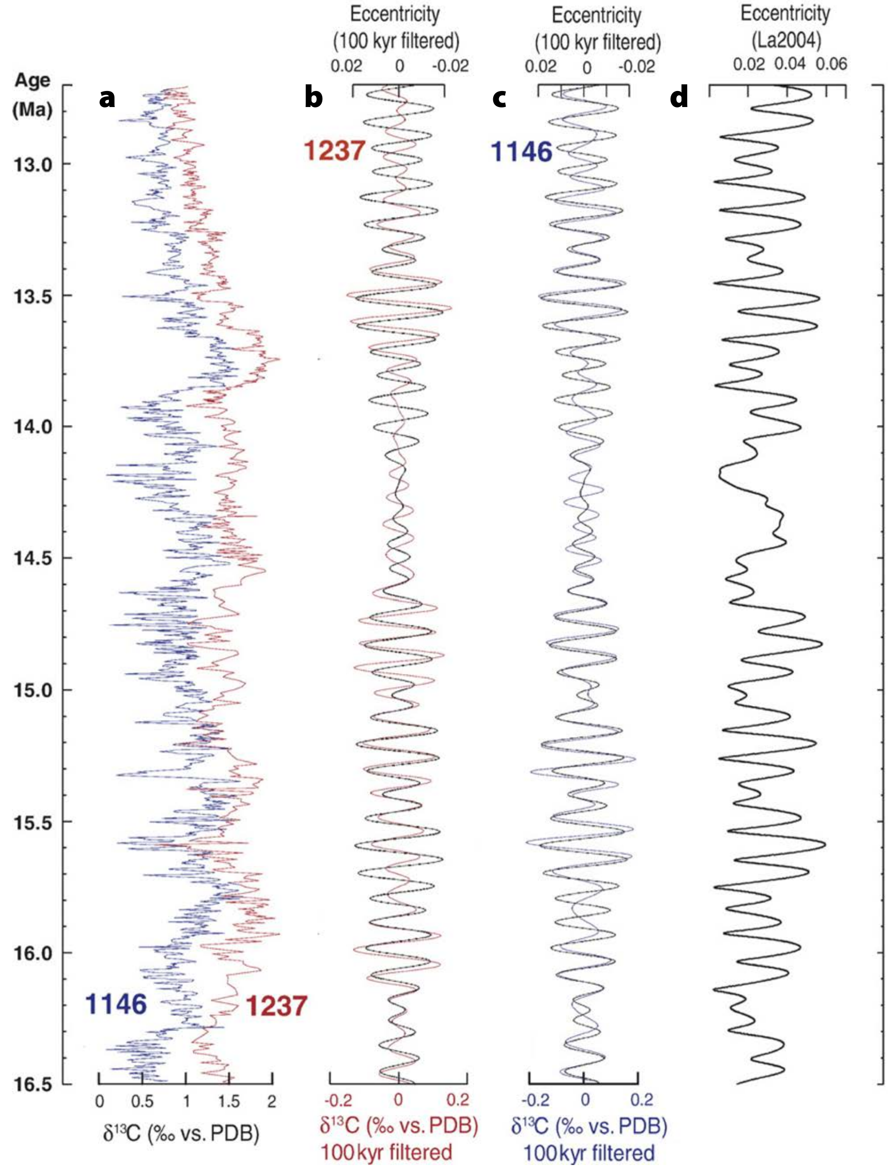


FIGURE 7. Precession-band phase wheel. (a) Example: Time series of a forcing parameter (red) operating on a 23,000-year cycle, and climate response (blue) that lags the forcing by one-fourth of a cycle, or 58,000 years. On the phase wheel, the forcing time series is represented as a red dot, while the lagged climate response is represented by a blue vector. Time lags are measured in the clockwise direction. (b) Precession band response of late Pleistocene summer monsoon reconstructions from the Indian and East Asian systems plotted relative to potential forcing parameters. OMZ = oxygen minimum zone. NH = Northern Hemisphere. SH = Southern Hemisphere.

FIGURE 8. Eccentricity rhythms in benthic foraminiferal $\delta^{13}C$ in the middle Miocene at ODP Site 1146, South China Sea, and IODP Site 1237, Southeast Pacific. (a) Benthic foraminiferal $\delta^{13}C$ at Sites 1146 and 1237. (b–c) Comparison of 100,000 year filtered 1237 $\delta^{13}C$ (red; b) and 1146 $\delta^{13}C$ (blue; c) with eccentricity from the La2004 numerical solution (black). (d) Eccentricity (Holbourn et al., 2007).



sediments. ODP 1146 is located in the Southeast Asian monsoon region and IODP 1237 in the South American monsoon region. Their common feature in responding to eccentricity forcing may be indicative of a common "global" monsoon origin (Figure 8; Holbourn et al., 2005, 2007) over these long timescales.

The 400,000-year eccentricity cycles are also observed in the Pliocene carbon isotopes and carbonate preservation in the South China Sea and Bay of Bengal, as well as in eolian dust records of the Arabian Sea (Figure 9). The strong imprint of the 400,000-year cyclicity in these low-latitude climate proxy records is interpreted in terms of a response to low-latitude insolation changes and hence monsoon variability. Similar to the Miocene records, the long eccentricity cycles in the Pliocene carbon reservoir, and during other geological periods, again may point to a common driver, the "global" monsoon. Although all of the Pliocene records show maximum $\delta^{13}C$ values at the eccentricity minima every 400,000 years, this $\delta^{13}C$ max-400,000-year relationship became obscured after ~1.6 million years in the Pleistocene, probably associated with restructuring of Southern Ocean circulation (Figure 9; P. Wang et al., 2010).

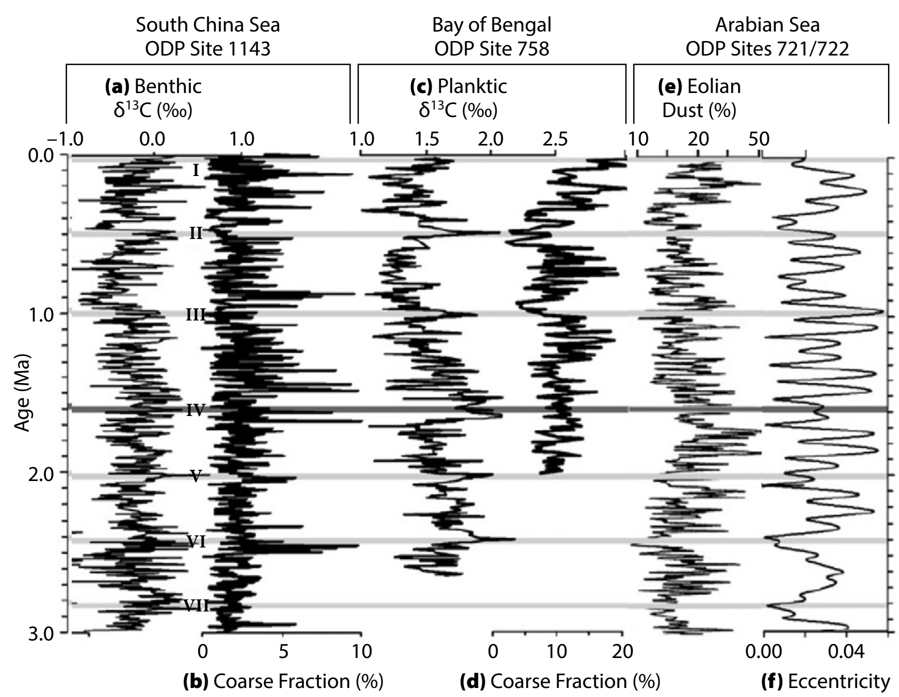


FIGURE 9. Long eccentricity cycles in carbon isotope and paleomonsoon records over the past 3 million years (from B. Wang et al., 2003). South China Sea, ODP Site 1143: (a) benthic carbon isotope (‰), (b) coarse fraction in sediments (%). Bay of Bengal, ODP Site 758: (c) planktic carbon isotope (‰), (d) coarse fraction in sediments (%). Arabian Sea, ODP Sites 721/722: (e) Eolian dust (%), (f) Eccentricity (P. Wang et al., 2010).

MILLENNIAL-SCALE VARIABILITY

Typically, suborbital climate variations of the late Quaternary are the focus of high-temporal-resolution studies that analyze short deep-sea piston cores recovered by conventional research vessels. In contrast, the focus of scientific ocean drilling expeditions is recovery of much longer sediment records. In those longer cores, millennial to centennial variability is recorded in deep time as evidenced by the alternations of dark and light layers in deepwater sediments of the Sea of Japan in cores from ODP Legs 127/128 and IODP Expedition 346. Because of the semi-enclosed nature of the Sea of Japan basin, periodic sea level fluctuations influence water column stratification, leading to euxinic bottom water conditions (water that is both anoxic and sulfidic) characterized by meter-thick dark layers deposited during glacial maxima (Tada et al., 1999, 2015, 2018). Furthermore, the alternating centimeter- to decimeter-scale dark and light layers reflect millennial-scale variations that can be associated with Dansgaard-Oeschger cycles (rapid climate fluctuations) during colder glacial periods, with each dark layer corresponding to an interstadial (i.e., the less cold, short periods within these cycles). Here, the critical mechanism involves strong modulation of salinity, nutrient supply, and strength of inflow through Tsushima Strait caused by changes in the discharge rate of monsoonal rivers flowing into the East China Sea.

Millennial-scale variations in the Sea of Japan were first observed through analysis of alternations of dark and light layers in the Quaternary section of sediment cores recovered by ODP Leg 127/128 in 1989 (Figure 10; Tada et al.1999). In 2013, IODP Expedition 346 extended the high-resolution record back to the Miocene, resulting in a long sediment sequence dating back ~12 million years (Figure 11; Tada et al., 2015). Thanks to the new half piston core system engineered by the *JOIDES Resolution* Science

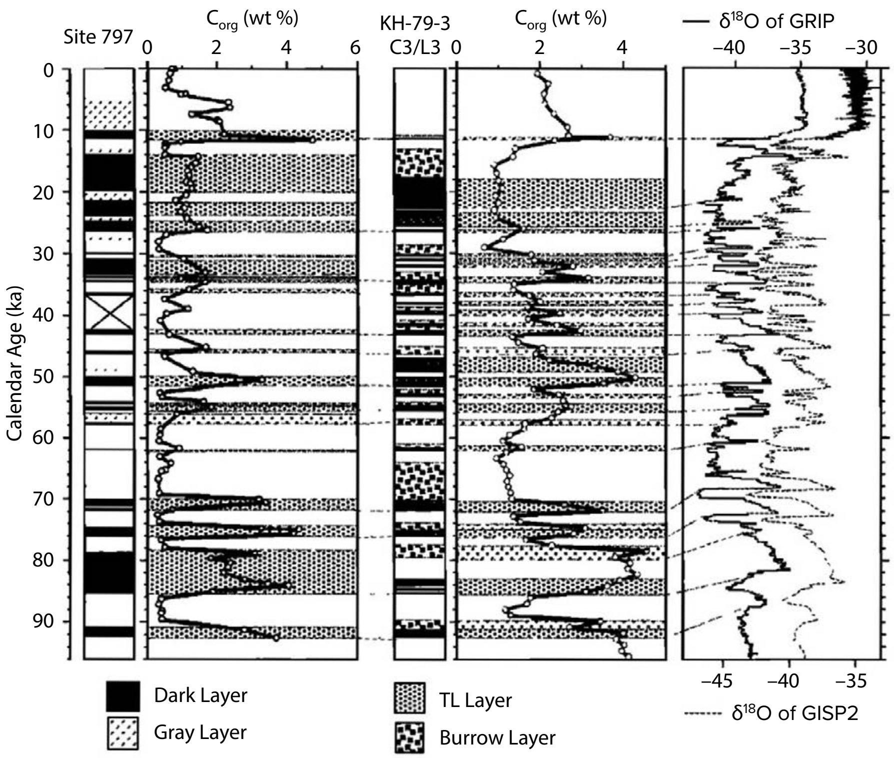


FIGURE 10. Millennial-scale variability of the East Asian monsoon determined from deep-sea records of the Sea of Japan. Comparison of the dark and light layers and their C_{org} profiles at ODP Leg 127, Site 797 and Core KH79-3 with $\delta^{18}O$ records from the Greenland Ice Core Project (GRIP) and Greenland Ice Sheet Project Two (GISP2) (Tada et al., 1999).

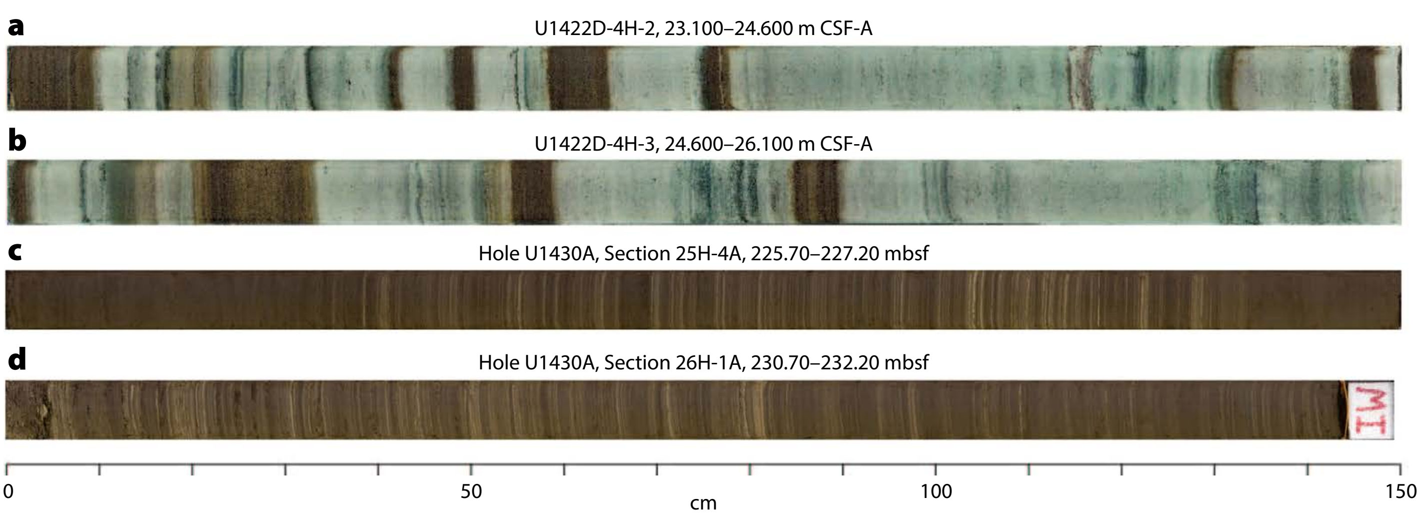


FIGURE 11. Representative dark and light layers in Sea of Japan cores. (a–b) Pleistocene section at IODP Site U1422 (with the color contrast enhanced). (c–d) Miocene section at IODP Site U1430 (Tada et al., 2015).

Operator, the deepest continuous piston core record in DSDP/ODP/IODP history (490.4 m) was recovered in Hole U1427A during IODP Expedition 346. The total 6,135.3 m of core provides a wealth of sediment to enable assessment of the extent to which the Plio-Pleistocene uplift of the Himalaya and Tibetan Plateau, and/or the emergence and growth of the Northern Hemisphere ice sheets, or the establishment of the two discrete modes of westerly jet stream circulation, caused the millennial-scale variability of the East Asian summer monsoon and amplification of Dansgaard-Oeschger cycles (Murray et al., 2014; Tada et al., 2015, 2018).

Highly resolved millennial-scale variability has also been documented from the Arabian Sea OMZ (ODP Site 722B on Leg 117; Higginson et al., 2004) as well as East China Sea surface waters (IODP Site U1429 on Expedition 346, Figure 12; Clemens et al., 2018). These sediment records further illustrate the strong influence of high-latitude North Atlantic dynamics on the low-latitude monsoon systems, presumably via an atmospheric teleconnection associated with the planetary Westerlies.

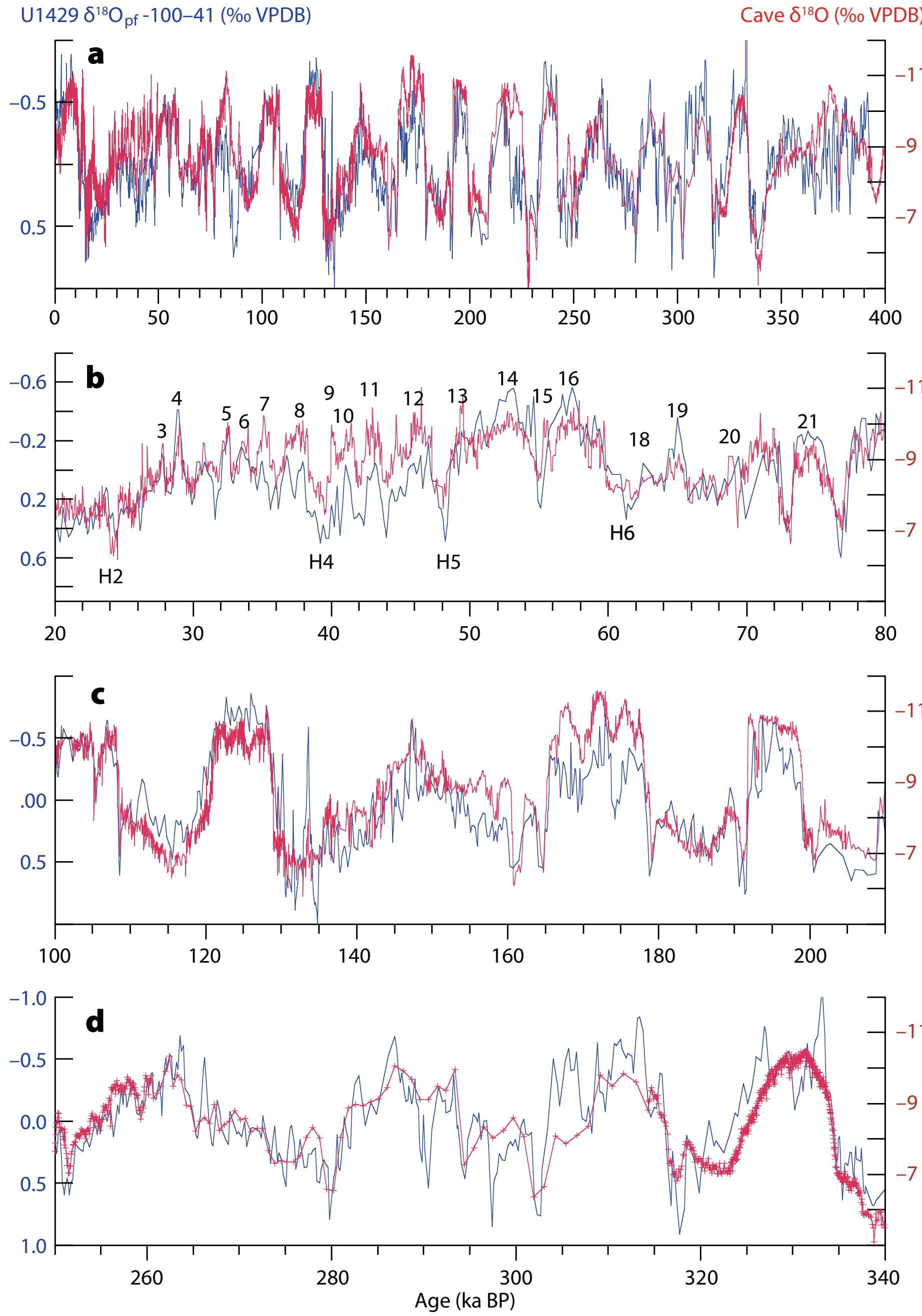


FIGURE 12. Millennial-scale structure in notched $\delta^{18}O_{pf}$ compared to $\delta^{18}O_{cave}$. (a) Notched IODP Site U1429 $\delta^{18}O_{pf}$ on the cave-based age model. (b) Expanded 20,000–80,000 years ago interval with millennial-scale Dansgaard–Oeschger (DO) and Heinrich events numbered. (c) Expanded 100,000–210,000 years ago interval. (d) Expanded 250,000–340,000 years ago interval showing structure not previously resolved in $\delta^{18}O_{cave}$. *From Clemens et al. (2018)*

A NEW CHALLENGE FOR FUTURE SCIENTIFIC OCEAN DRILLING

Over the last two decades, there has been a dramatic increase in research activities devoted to monsoon variability. In addition to modern-day satellite records that have extended monsoon observations beyond the continents and into data-scarce oceanic regions, detailed records from speleothems, ice cores, and deep-sea and terrestrial sediment records have enhanced the resolution of monsoon proxy records to an unprecedented level. Traditionally, monsoon variability was studied almost exclusively on regional scales. However, the "global monsoon" concept has now been introduced as a global-scale seasonal reversal of the three-dimensional monsoon circulation that can be associated with the migration of rainfall in the monsoon trough and the Intertropical Convergence Zone (Trenberth et al., 2000; B. Wang and Ding, 2006).

In view of the ever-increasing complexity of monsoon variability in paleoclimate records, international working groups have been organized to review research progress and perspectives. Twenty years ago, the SCOR-IMAGES Evolution of Asian MONSoon (SEAMONS) working group was set up to assess the current status and outstanding issues in paleoclimate study of the Asian monsoon (Clemens et al., 2003; P. Wang et al., 2005). In 2007, the Past Global Changes (PAGES) project "Global Monsoon and Low-Latitude Processes: Evolution and Variability" working group was established, bringing together paleo- and modern-day climatologists in an effort to improve our understanding of the dynamics of monsoon variability (P. Wang et al., 2012, 2014, 2017). In September 2017, the IODP-PAGES workshop on "Global Monsoon in Long-term Records" was held in Shanghai, China, to review the achievements of the most recent monsoon-related IODP expeditions (P. Wang et al., 2018). Future IODP efforts will need to significantly extend the spatiotemporal coverage of monsoon records, as high-resolution deep-time monsoon records are required to reveal monsoon changes at the "hot-house to ice-house" transitions, as well as the tectonic background of when and how the modern monsoon systems was established.

These new program emphases will be enhanced by community efforts to continue to develop, test, and verify new proxies designed to better assess the impact of seasonality on our interpretation of past monsoonal circulation (summer vs. winter circulation) and better assess the extent to which proxies can differentiate changing wind patterns, rainfall patterns, and surface circulation patterns, all of which are related to changing monsoonal circulation.

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