Marine Proxies Of Paleomonsoon: Emphasis On Indian Monsoon System

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Abstract

Marine proxies are the most prominent tools in the history of the monsoon. Palaeomonsoon is the seasonal movement of wind belts and differential heating of land and water caused by the interaction between the ocean and atmosphere. The Indian monsoon is distinct from other monsoon systems in terms of its focal points, associated air masses, and mechanism for precipitation. It has two distinct phases: the southwest monsoon (June to September), which brings the majority of the precipitation to India and the northeast monsoon (November to February). The tropical monsoon has been proposed as a major modulator of the northern hemisphere climate and a major player at the end of the last ice age. Monsoon rainfall is recorded in sediments deposited on the ocean floor from the Arabian Sea region. Humidity and temperature are measured through physical and chemical parameters, and isotopic compositions are used to understand temperature, atmospheric composition, and ocean salinity. Microfossil assemblages and abundances of species are also important indicators of how physical and chemical factors affect biota.

Keywords: Paleomonsoon, Sedimentological Proxies, Palaeosols, Paleontological Proxies, Climate Changes

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1. Introduction

A circulation that switches from summer to winter and vice versa every six months is referred to as a palaeomonsoon. It was previously explained by the seasonal movement of tropical and subtropical wind belts and the differential heating of land and water. Long-term historical monsoon records can be used to better understand monsoon dynamics, particularly the interaction between the ocean and the atmosphere. An overall picture of monsoon variations in the Indian subcontinent and neighbouring oceanic regions can be obtained by comparing historical monsoon records from both terrestrial and marine domains. The monsoon wind phenomenon and its peculiar reversing circulation were once assumed to be caused by the temperature differential between land and sea. However, the monsoon circulation has a number of peculiar features, including its burst or rapid change from the dry to the wet season and the illogical patterns of rainfall associated with it. To better comprehend monsoon dynamics, particularly the interplay between the ocean and the atmosphere, long-term historical monsoon records can be employed. The monsoon records from these archives could, however, have biases as a result of various physical, chemical, and biological processes. Comparing historical monsoon records from marine realms can provide a broad overview of monsoon variations in the Indian subcontinent and surrounding maritime regions.

2. The Indian Monsoon System

In comparison to the rest of Asia, the Indian subcontinent's monsoon system is very different. The Indian monsoon is distinct from other monsoon systems in terms of its focal points, associated air masses, and mechanism for precipitation. The majority of people living in the area rely mostly on agriculture for their income and way of life. The monsoon in this area has two distinct phases: the southwest monsoon (from June to September), which brings the majority of the precipitation to India, and the northeast monsoon (from November to February), which brings heavy rains to the area south of the equator and the equatorial Indian Ocean. The tropical monsoon has been proposed as a major modulator of the northern hemisphere climate as well as a major player at the end of the last ice age. Understanding the elements that affect the monsoon is crucial because it will aid in improving the global circulation models that are used to predict future changes in the monsoon. The cooling of the Asian landmass after the initial rain shows that the land-ocean thermal contrast cannot support the sustained "breeze," which provides precipitation over a number of months. Blanford (1884) first hypothesized, and Vernekar et al. (1995) later proved that there is an inverse link between snow cover over the Himalayas during the winter and spring seasons and summer monsoon precipitation. Flohn (1968) proposed that the monsoon-producing air circulation is sustained by the western Tibetan Plateau and orographically released latent heat over southern Tibet. The relevance of high mountains in the north in both starting and maintaining the monsoon was validated by modelling studies. In comparison to orography east of 80 degrees east, orography west of 80 degrees east has a greater influence on summer precipitation. Sikka & Gadgil (1980) first postulated the monsoon as a manifestation of the north-south migration of the inter-tropic convergence zone, and Gadgil (2003) later verified this idea.

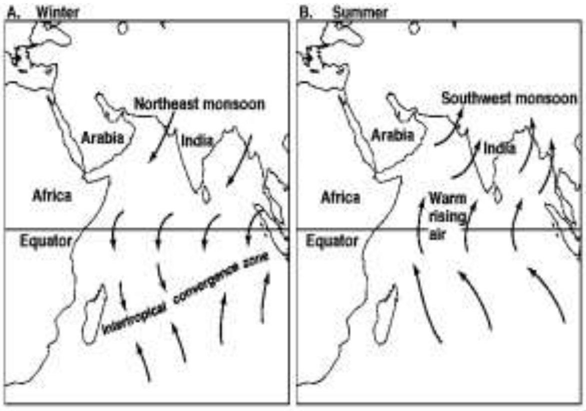
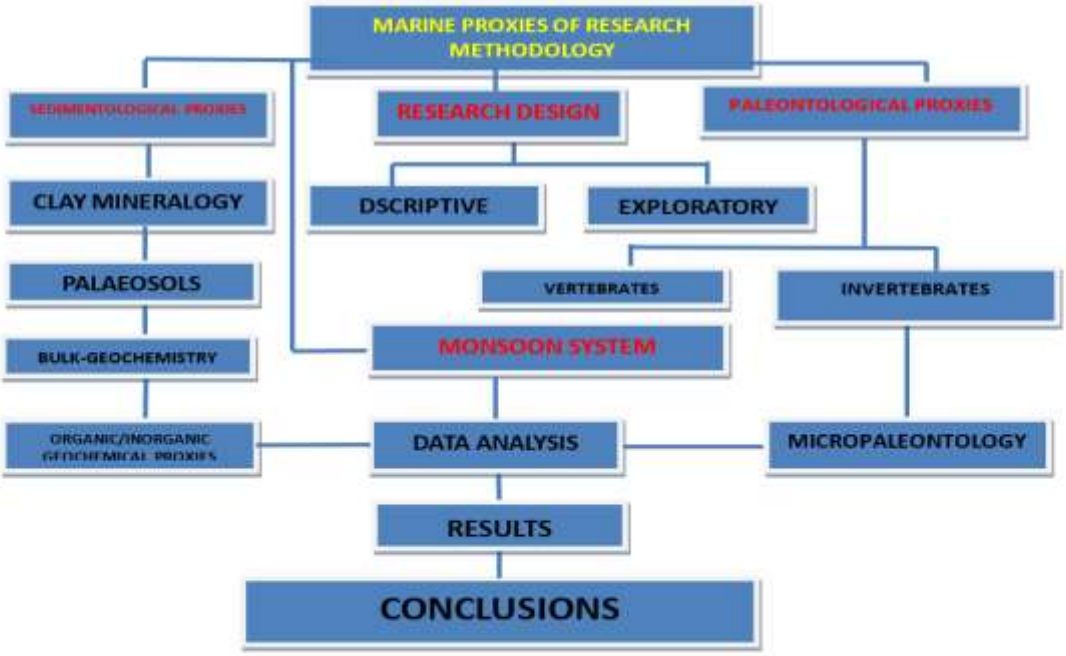


Fig.1: Indian Winter (A) and Summer (B) system through wind direction.

Marine Proxies of Paleomonsoon

The evidence of monsoon rainfall is recorded in a number of proxies both across the land and maritime region, but the sediments deposited on the ocean floor from the Arabian Sea region are undoubtedly the most trustworthy continuous record of the monsoonal fluctuation. Since we have been recording climate characteristics with instruments since the modern era, we are unable to directly witness the climates of the geological past Ghil, M. (2002). Humidity and temperature are the main factors that are measured. Through analyses of physical and chemical parameters in the sedimentary deposits, such as clay mineralogy, grain size distribution, heavy minerals, organic biomarkers, and isotopic proxies like isotopes in the ice core, alkenones, sedimentary organic fraction, inorganic carbonates, and organic deposits, such information can be indirectly retrieved from sedimentary archives. In order to comprehend temperature, atmospheric composition, and ocean salinity, respectively, isotopic compositions establish a direct link. In addition to this multi-parameter approach, the distribution of microfossil assemblages and abundances of specific species from maritime platforms are significant indicators of how physical and chemical factors affect the biota.



The creation and dependability of climate proxies are essential to analyzing paleoclimate variability using the geological record. An overview of the major common geological archives and their proxy data that document previous variations in the monsoon. This proxy review also shows some of the potential difficulties in interpreting particular proxies. Monsoon proxies can generally be classified into two categories based on the main monsoon feature they address: those linked to monsoon winds (direction, strength, and persistence) and those connected to monsoon-induced precipitation. From terrestrial and marine archives found on the Indian subcontinent and its neighbouring oceans, past monsoon shifts have been reconstructed. The early prior summer monsoon strength observations from the western Arabian Sea were based on the increased abundance of planktic foraminifera Globigerina bulloides in cold, nutrient-rich water that rises to the top in response to southeasterly winds. According to Clift & Webb (2019), these winds are what cause the summertime precipitation in the Indian subcontinent by bringing moisture to the area. After that, a wide range of organo-bio-geochemical proxies, such as grain size, magnetic susceptibility, clay mineralogy, total organic carbon content, major, minor, and trace element composition of the sediments, and stable isotopic ratio of specific elements, have frequently been used to infer past monsoon changes from cores collected in the Indian Ocean.

3.1 Sedimentological Proxies

Sedimentology can shed light on loess sediment, where the strength and capacity of wind transport, source areas, and land surface conditions are reflected in the modal particle size.

3.1.1Clay Mineralogy

According to Chamley 1989; Sellwood et al., 1993; Diester-Haass et al. 1998, clay mineral composition in the marine and terrestrial record indicates weathering processes in the catchment area and basin, which are adjacent to the depositional setup. As an illustration, a study on the marine sedimentary record from southern latitudes documented a trend in the abundances of smectite, chlorite, and illite. According to Ehrmann et al. (2005), the change from humid to sub-polar and polar conditions is indicated by a diminishing proportion of crystallized smectite and chlorite and an increasing amount of illite in sediments. Low gibbsite concentration in soils deposited in glacial terrain, according to Benn & Ballantyne (1994), can also be used to date the deposit of cosmogenic isotopes.

3.1.2 Palaeosols

As a surrogate for vegetation and climate changes, stable isotope (oxygen and carbon) ratios in paleosol carbonate nodules (Ghosh et al., 2006) and related organic matter have been employed. The carbon isotopic content of carbonate nodules indicates the existence of C3, C4, and CAM vegetation types, whereas the oxygen isotopic composition of carbonate nodules indicates the temperature and salinity condition of ambient water (Quade & Cerling,1995). Paleosols have been recommended as a key palaeoclimatic proxy, particularly for estimating palaeo-precipitation, by Sellwood & Price (1993). A sedimentary record's palaeosol content indicates periods of little or no sedimentation. Their mineral and chemical makeup reveals the interaction of their terrigenous clastic source sediments and weathering processes, which might be physical, chemical, or biological.

3.1.3 Bulk Geochemistry

The loss or gain of chemically unique sources, such as ophiolite belts; carbonate platforms; granite plutons; etc., from drainage is reflected in the bulk geochemistry. Chemical alterations in the weathering environment can be found by carefully analyzing elemental ratios that are sensitive to sedimentary processes.

2.1.4 Organic/ Inorganic Geochemical Proxies

Specifically, Mg/Ca, Ba/Al, and Cd/Ca display a range of temperature and productivity responses related to monsoon circulation. Organic geochemical proxies, which can be affected by changes in winds, mixing, and precipitation, reflect temperature, productivity, nutrient uptake, and water column structure. These proxies include organic carbon percentage and flux, opal percentage, N-15, and C-13 in near-surface dwelling planktic foraminifera, Alkenone, SST, TEX86, and compound-specific biomarkers.

3.1.5 Stable Isotope Proxies

The application of stable isotopes as environmental proxies is based on the fractionation ofisotopes by mass. It means that the isotope ratios are constant in nature; rather, they vary as a consequence of phase transition during different natural cycles, and their determination allows for the tracing of these changes. Importantly, it is possible to quantify the fractionation behaviour and to express it as fractionation factors. Moreover, these fractionation factors are a function of temperature during the fractionation process. Fractionation factors and their temperature dependence have to be known in order to conduct paleothermometry using carbonate deposits.

Isotope fractionation occurs in two mechanisms which are equilibrium and disequilibrium fractionation. Equilibrium means that constant isotope proportions occur between considered phases. The relative isotope abundance is controlled by temperature and hence the energy content of the reacting system. The kinetic isotope effects are associated with incomplete and unidirectional processes like enhanced degassing or rapid carbonate precipitation, among others, e.g. Evaporation accounts for disequilibrium fractionation between speleothem carbonate drip water.

3. Paleontological Proxies

Allmon (2016) is the earliest known instance of the empirical use of fossils and fossil assemblages as palaeoclimate indicators, and traditional biostratigraphic literature even acknowledged the importance of these indicators. Monsoon intensity across time has been successfully reconstructed using sedimentary data from the ocean. The biological, chemical, and sedimentological factors have been recognized as crucial for comprehending how strongly upwelling events are correlated with the force of monsoonal winds. In terms of wind speed across time, monsoonal variability can thus be limited. The strong seasonal upwelling is brought on by the south-westerly monsoon winds coming from the Arabian Sea (Anderson & Prell, 1993). Foraminiferal species that are unique to upwelling regions can be found in the Arabian Sea sediments. Because the majority of these species only occur in cool, temperate waters, their presence and abundance in sediment records serve as an indicator of upwelling (index) parameters. High-quality core-top data banks were supplied by Cullen and Prell (1984) to identify, create, and assess proxies for monsoonal upwelling. Based on the examination of 251 core-top samples, the northern Indian Ocean depicts the distribution of planktic foraminiferal species that live in surface waters and serves as a tool for paleoceanographic reconstructions. The assortment of foraminiferal species captures changes in surface water hydrographic conditions along with isotopic ratios and trace element concentration (e.g. Wefer et al., 1999; Thunell & Sautter, 1992; Kennett & Srinivasan, 1983; Savin et al., 1985). One of the most popular instruments for retracing historical variations in sea surface temperature and salinity is the oxygen and carbon isotope composition of planktic foraminifera shells (18Oshell, 13Cshell) (King & Howard, 2005). According to several studies (Prell et al., 1992; Overpeck et al., 1996; Gupta et al., 2003), species with high concentrations, such as Globigerina bulloides, reflect upwelling conditions in tropical oceans. Although deep habitat reorganization brought on by climate change and the 18O of planktic foraminiferal calcite records permit reconstruction of global surface temperatures, these records suffer (MacLeod et al., 2005). Neogloboquadrina dutertri, along with G. bulloides, is a key part of the planktonic foraminiferal group found in the Arabian Sea upwelling region (Be & Hutson, 1977). According to Be and Hutson (1977), the oligotrophic subtropical-tropical surface waters are where the Globigerinoides species (such as Globigerinoides sacculifer and Globigerinoides ruber) can be found. Higher frequencies of Globigerinoides are associated with surface water conditions that are distinct from upwelling conditions (Kroon et al., 1991). The measurement of parameters like 18O reflecting either temperature or ice volume influence allowed for the reconstruction of paleotemperature using benthic foraminifera from several sites in the Pacific, Atlantic, and Indian Oceans (Zachos et al., 2001). Because they can adapt to shifting environmental conditions, benthic foraminifera can live in a variety of maritime settings. Their calcium carbonate shells serve as a substantial carbon sink on a worldwide scale. Additionally, they have significant potential for fossilization due to their calcareous or agglutinated tests. Based on observations from a contemporary environmental niche, benthic foraminifera thus constitutes a crucial tool for reconstructing deep-sea paleoceanography and palaeoclimatology (Gupta & Srinivasan, 1992). Past monsoon shifts have been reconstructed from terrestrial and marine archives discovered on the Indian subcontinent and the adjacent oceans. Based on the increased abundance of planktic foraminifera Globigerina bulloides in nutrient-rich cold water that rises to the surface in response to winds blowing from the southwest, the early before summer monsoon strength data from the western Arabian Sea were derived. These winds are responsible for the region's midsummer precipitation because they transport moisture to the Indian subcontinent (Kroon et al., 1991; Prell et al., 1992). It has been possible to deduce past monsoon changes from cores taken in the Indian Ocean by looking at the characteristics of marine microfossils, grain size, magnetic susceptibility, clay mineralogy, total organic carbon content, major, minor, and trace element composition of the sediments, as well as a stable isotopic ratio of particular elements. Numerous pale monsoon records from the Indian Ocean have been reconstructed using microfossils like foraminifera, radiolarians, diatoms, ostracodes, coccolithophores, pollens, spores, alkenone, corals, and other microfossils. Also used to explain temporal changes in pteropod abundance and diversity are changes in relative abundance, morphology, species assemblage and diversity, shell weight, stable isotopic ratio, and trace metal ratio of the fossil calcareous shells. Trees (ring width and stable isotopic composition), peat deposits, ice cores, loess-paleosol sequences, and speleotherm.

4. Initiation of Monsoon System

The Ocean Drilling Programme and Deep Sea Drilling Project have drilled sites that have allowed researchers to recreate long-term previous monsoon records. These data have been used to infer the beginning, significant phase shifts, and seasonality variations of the Indian monsoon. There is disagreement over when the Indian monsoon system should start (Clift et al., 2008). However, the existence of typical upwelling indicator fauna in the western Arabian Sea strata shows that the summer monsoon may have begun at around 8.2 Ma and intensified significantly at that time (Kroon et al., 1991; Prell et al., 1992). Based on historical monsoon records from China, the Indian and North Pacific oceans, and the Himalaya-Tibetan plateau, it was hypothesized that the monsoon's onset (9–8 Myr ago) and subsequent evolution, as well as the plateau's phased uplift, were closely related (An et al., 2001). However, Gupta et al. (2004) argued that the high productivity event at 10-8 Myr, which is thought to be a sign of the beginning of the Asian monsoon, may have been caused by stronger winds brought on by global cooling and the expansion of the Antarctic ice sheets rather than by the uplift of the Himalaya-Tibetan plateau, which would have increased nutrient delivery and upwelling. A comparable monsoon circulation system is similar to that of today, with strong summer and winter seasonality, established by ~2.8 Ma, as inferred from the increased abundance of benthic foraminifera indicative of seasonal food supply (Gupta and Thomas, 2003). According to the increasing abundance of benthic foraminifera suggestive of seasonal food supply, a monsoon circulation system equivalent to that of today with high summer and winter seasonality was developed by around 2.8 Ma (Gupta and Thomas, 2003).

5. Glacial-Interglacial Changes in Monsoon and its link with Global Climate

Solar radiation, Earth's main energy source, changed latitudinally during the Quaternary. Milankovitch cycles are cyclic insolation shifts with 100, 41, and 23 ka periods (Hays et al., 1976). Since solar radiation drives many physical processes, attempts have also been made to investigate how Milankovitch scale fluctuations in solar radiation affect monsoon strength. Marine and terrestrial proxy monsoon records suggested a significant summer monsoon during obliquity maxima and 125° (8 kyrs) after precession minima (Clemens et al., 2010). Long-term records indicate glacial-interglacial monsoon strength variations throughout the Pleistocene (Clemens and Prell, 1991). The monsoon intensity during the last glacial-interglacial transition has been thoroughly recreated using short gravity cores (<6 m) from the continental shelf and lakes. Several proxy records from the Arabian Sea and the Bay of Bengal imply summer monsoon decrease and winter monsoon augmentation during glacial eras (Figure 2). The latest deglaciation had a weak monsoon interlude followed by a brief, vigorous one. The Bølling-Allerød had more summer monsoon precipitation than the Younger Dryas and the previous glacial period, probably due to North Atlantic climate shifts (Rashid, 2007). High-resolution total organic carbon (a proxy for past productivity, which is linked to monsoon intensity) and surface-dwelling planktic foraminiferal -18O records indicated a strong link between high latitude processes and monsoon in the Indian subcontinent and adjacent regions, with distinct Dansgaard-Oeschger cycles during the last glacial cycle (Schulz et al., 1998; Kudrass et al., 2001). High-resolution monsoon records and tropical and high-latitude physical processes reveal a millennial-scale relationship between the northern hemispheric climate and the monsoon. Tropical ice core records also show that the tropical hydrological cycle controls global atmospheric CH4 concentration.

6. Monsoon Changes during the Holocene

As inferred from both the marine and terrestrial records, a summer monsoon optimum during the early Holocene was followed by changing summer monsoon intensity for the majority of the Holocene (Rashid et al., 2007). Throughout the Holocene, weak summer monsoons have coincided with the North Atlantic cold periods, including the most recent climate changes from the Mediaeval Warm Period to the Little Ice Age, according to the centennial-scale monsoon records (Kotlia et al., 2012). The south-eastward movement of Harappan civilization settlements in the Indus Valley at 4.2 ka BP was accompanied by a change in living habitats from a highly organized urban phase to a phase of smaller settlements, according to high-resolution monsoon records (Staubwasser et al., 2003). Tree rings (Yadav, 2013), speleothems (Kotlia et al., 2012), and corals (Ahmad et al., 2011) have all been used to infer variations in the monsoon on an annual to sub-annual scale over the past several thousand years. From both marine and terrestrial data, both short- and long-term regular cyclic fluctuations in monsoon intensity have been inferred, with a frequency ranging from a few decades to a few millennia (Saraswat et al., 2014). Even tiny (1%) decadal to centennial-scale changes in insolation can result in substantial changes in the tropical monsoon, according to a robust link between summer monsoon winds derived from foraminiferal proxies and sunspot numbers. Throughout the Holocene, the strength of the summer monsoon fluctuated, with weak monsoons occurring when the North Atlantic was cold. At 4.2 ka BP, the monsoon changed, and the Harappan civilization's settlements migrated southeast, according to high-resolution monsoon records. The number of sunspots and summer monsoon winds are related, according to foraminiferal proxies.

7. Quantitative Estimation of Paleomonsoon

Since rainfall evaporation over the ocean and changes in riverine influx in response to precipitation on land directly affect seawater salinity in both the Bay of Bengal and the Arabian Sea, it is a helpful indicator of previous monsoon severity. Quantitative estimates of past seawater salinity calculated by correcting the stable oxygen isotopic ratio of the surface-dwelling planktic foraminifera for global ice volume contribution better constrain pale monsoon changes because sea surface temperature is estimated from the Mg/Ca ratio in the same species (Saraswat et al., 2014) or alkenone unsaturation ratio (Saher et al., 2009). A change in surface runoff as determined by the Ba/Ca ratio of planktic foraminifera that live on the surface is also a reliable indicator of past monsoon intensity. In comparison to the Holocene, the surface salinity at the last glacial maximum was higher in the northern Bay of Bengal by about 2 practical salinity units (PSU), the equatorial Indian Ocean by about 2.5 psu, and the Bay of Bengal by about 1 psu (Cullen, 1981). This suggests a diminished summer monsoon. The equatorial Indian Ocean's surface seawater salinity during the penultimate interglacial period was around one psu lower than it was throughout the Holocene, implying that there was more precipitation than evaporation. Numerous researchers have deduced that there was a significant geographical variation in surface salinity during the LGM compared to the Holocene, with a non-uniform change in salinity over the northern Indian Ocean, suggesting different summer and winter monsoon intensities. However, there is a lot of ambiguity surrounding these absolute salinity values, so they should be used with caution. Tree rings are utilized to estimate high-resolution variations in precipitation in addition to the use of seawater salinity as a proxy for quantitative reconstruction of previous monsoons (Yadav, 2013). However, the majority of the tree-ring-based historical precipitation records are only available for the Late Holocene. The strength of the summer monsoon has declined during 3–4 Ma, according to numerous marine and terrestrial records. However, no concrete evidence for this connection has been found. Magnetic susceptibility and dust blown by westerlies at ODP Site 885/886 in the North Pacific began to grow at a faster pace after 4 Ma and considerably earlier than the start of NHG at about 2.6 Ma. Additionally, dust transported by winds is seen to accelerate in its buildup in the North Pacific as well as the Chinese Loess Plateau, an event connected with monsoon intensification. Additional South China Sea data also support greater upwelling caused by the monsoon at roughly 8 Ma. The upwelling G. Bulloides record from Oman, another upwelling-related foraminifer from the South China Sea, and dust flux to the North Pacific are three distinct monsoon proxies across Asia.

8. Monsoon Tracers from the Geological Records

The concentration of the planktonic foraminifera Globigerina bulloides, excess barium flux, lithogenic grain size, and records of biogenic opal flow are four tracers that are connected to the severity of the monsoon through separate pathways in the marine and atmospheric system (Fig. 2a). We may more accurately assess the temporal relationships between historical monsoon strength and changes in both conceivable internal (such as latent heating and boundary condition) and external (such as solar) forcing mechanisms. Globigerina bulloides, a planktonic foraminifer that is generally found in subpolar environments, is also widely distributed in tropical upwelling areas that include cold, nutrient-rich water. In a large portion of the modern ocean, high opal flow is linked to monsoon circulation as an indicator of silica productivity linked to monsoon-induced upwelling. The low-level southwest monsoon and shamal wind system's potential for transport links the lithogenic component's grain size to monsoon wind strength. Larger lithogenic dust particles are transported by stronger winds from the Somali and Arabian Peninsula desert source regions. High concentrations of barium are seen in sediments beneath productive waters. Due to its resistance to dissolution processes that influence both carbonate and siliceous sedimentary components, this biogeochemical tracer is employed. Aeolian clays have excess barium flow, which can be used as a proxy for biogenic production in the Arabian Sea by normalizing it for terrestrial barium. Minor variations in the precise timing and relative amplitude can be attributed to a variety of factors that are not always directly related to monsoon fluctuation, such as differential opal and carbonate dissolution, changes in the location of the dust source, sediment winnowing, and ecosystem dynamics.

9. Monsoon and Associated Oceanographic Effects

The surface oceanic circulation in the northern Indian Ocean (the Arabian Sea and the Bay of Bengal) changes direction with the shifting wind patterns during the summer and winter monsoons (Wyrtki 1973; Schott and McCreary Jr 2001). Along the Somalian and Omani coasts, there is intense upwelling with a transfer of 1.5–2 Sv in the upper 50m. The upwelled water typically has a temperature range of 19 to 24 C (Schott and McCreary Jr. 2001). The Ekman divergence caused by the strong winds flowing parallel to the shore is thought to be the cause of this significant coastal upwelling. Under the influence of the Findlater jet wind stress forcing and the Ekman pumping, the central Arabian Sea displays a bowl-shaped mixed layer that is deepening. The high salinity surface waters in the northern Arabian Sea are subducted as a result of the cold, dry northeast monsoon winds and Ekman pumping. As nutrient-rich deeper water surfaces and the sea surface temperature (SST) falls by 4°C as a result of the upwelling zones between the Somalian and Omani coasts, significant biological and geochemical changes occur in this region. Along southwest India's coastline, there is also weak upwelling. Minor upwelling is seen in the northeastern Arabian Sea during the Northeast monsoon (Wyrtki 1973). Due to convective mixing in the northern Arabian Sea caused by the cold and dry NE monsoon winds, the mixed layer deepens to a depth of 100–125 metres. This results in nutrient injection and high productivity during the winter monsoon in this area. For the SW monsoon, NE monsoon, and intermonsoon seasons, the typical productivity values for the western Arabian Sea are 2.0, 1.0, and 0.5g C/m2/day, respectively. Similar production levels are typically 0.6, 0.3, and 0.2g C/m2/day during the SW monsoon, NE monsoon, and intermonsoon periods, respectively, in the eastern Arabian Sea. The moisture-laden SW monsoon winds are forced to ascend as they approach the Western Ghats, causing abundant precipitation and runoff into the nearby Arabian Sea, which significantly lowers the sea surface salinity (Sarkar et al. 2000). Due to the extremely low oxygen content over the whole Arabian Sea from 250m to 1250m water depths, denitrification occurs. The high oxygen consumption below the thermocline for the oxidation of organic matter provided by the high above-surface productivity is what causes the oxygen minimum zone (OMZ). A strong tropical thermocline (caused by relatively high SST, which inhibits the mixing of the oxygen-rich surface waters with the deeper waters) and the sluggish flow of the intermediate water with low oxygen content are other factors that sustain the OMZ. As a result, monsoon winds, the productivity they provide, and other climatically controlled variables like ocean ventilation rate interact to produce OMZ and denitrification. The Arabian Sea is ideally suited for analyzing historical changes in monsoon intensity because of such stark changes in the properties of salt water. The carbon isotopic composition of the seawater, which is stored in the calcitic shells of diverse foraminifera, is also affected by surface productivity, which can take many different forms, including organic, calcareous, and siliceous productivity. The oxygen isotopic composition of these shells is also altered by the SST and sea surface salinity, and these changes are preserved in the sea sediments. The denitrification intensity associated with changes in productivity can be determined by the nitrogen isotopic composition of sedimentary organic matter. In order to better understand previous variations in monsoon strength and the associated climatic shifts, it may be useful to look at the downcore variations of such proxies.

10. Conclusions

The origin and long-term evolution of the monsoon have been well documented. High-resolution centennial to sub-centennial scale records of qualitative changes in past monsoons have been reconstructed from both the Arabian Sea and the Bay of Bengal, as well as from the Indian subcontinent. These records are needed to assess the link between low and high-latitude processes and to infer the lead-lag relationship between monsoons and other climate processes. Cores collected from regions with high sedimentation should be targeted to collect good quality cores, but it is difficult to apply calcareous fossil-based proxies to reconstruct past monsoon changes.

References

1. Ahmad, S. M., Padmakumari, V. M., Raza, W., Venkatesham, K., Suseela, G., Sagar, N., ... & Rajan, R. S. (2011). High-resolution carbon and oxygen isotope records from a scleractinian (Porites) coral of Lakshadweep Archipelago. *Quaternary International*, *238*(1-2), 107-114.
2. Allmon, W. D. (2016). Darwin and palaeontology: A re-evaluation of his interpretation of the fossil record. *Historical Biology*, *28*(5), 680-706.
3. Anderson, D. M., & Prell, W. L. (1993). A 300 kyr record of upwelling off Oman during the late Quaternary: evidence of the Asian southwest monsoon. *Paleoceanography*, *8*(2), 193-208.
4. Bé, A. W., & Hutson, W. H. (1977). Ecology of planktonic foraminifera and biogeographic patterns of life and fossil assemblages in the Indian Ocean. *Micropaleontology*, 369-414.
5. Benn, D. I., & Ballantyne, C. K. (1994). Reconstructing the transport history of glacigenic sediments: a new approach based on the co-variance of clast form indices. *Sedimentary Geology*, *91*(1-4),

215-227.

6. Blanford, H. F. (1884). II. On the connexion of the Himalayas, snowfall with dry winds and seasons of drought in India. *Proceedings of the Royal Society of London*, *37*(232-234), 3-22.
7. Chamley, H., & Lille, U. (1989). Clay mineralogy.
8. Clemens, S. C., Prell, W. L., & Sun, Y. (2010). Orbital-scale timing and mechanisms driving Late Pleistocene Indo-Asian summer monsoons: Reinterpreting cave speleothem δ18O. *Paleoceanography*, *25*(4).
9. Clemens, S., Prell, W., Murray, D., Shimmield, G., & Weedon, G. (1991). Forcing mechanisms of the Indian Ocean monsoon. *Nature*, *353*(6346), 720-725.
10. Clift, P. D., & Webb, A. A. G. (2019). A history of the Asian monsoon and its interactions with solid Earth tectonics in Cenozoic South Asia. *Geological Society, London, Special Publications*, *483*(1), 631-652.
11. Clift, P. D., Hodges, K. V., Heslop, D., Hannigan, R., Van Long, H., & Calves, G. (2008). Correlation of Himalayan exhumation rates and Asian monsoon intensity. *Nature geoscience*, *1*(12), 875-880.
12. Cullen, J. L. (1981). Microfossil evidence for changing salinity patterns in the Bay of Bengal over the last 20 000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *35*, 315-356.
13. Cullen, J. L., & Prell, W. L. (1984). Planktonic foraminifera of the northern Indian Ocean: distribution and preservation in surface sediments. *Marine Micropaleontology*, *9*(1), 1-52.
14. Diester-Haass, L., Robert, C., & Chamley, H. (1998). Paleoproductivity and climate variations during sapropel deposition in the eastern Mediterranean Sea. In *Proceedings-Ocean Drilling Program Scientific Results* (pp. 227-248). National Science Foundation.
15. Ehrmann, W., Setti, M., & Marinoni, L. (2005). Clay minerals in Cenozoic sediment off Cape Roberts (McMurdo Sound, Antarctica) reveal palaeoclimatic history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *229*(3), 187-211.
16. Flohn, H., & Reiter, E. R. (1968). *Contributions to a meteorology of the Tibetan Highlands* (Doctoral dissertation, Colorado State University. Libraries).
17. Gadgil, S. (2003). The Indian monsoon and its variability. *Annual Review of Earth and Planetary Sciences*, *31*(1), 429-467.
18. Ghil, M. (2002). Natural climate variability. *Encyclopedia of global environmental change*, *1*, 544-549.
19. Ghosh, P., Garzione, C. N., & Eiler, J. M. (2006). Rapid uplift of the Altiplano revealed through 13C-18O bonds in paleosol carbonates. *Science*, *311*(5760), 511-515.
20. Gupta, A. K., & Srinivasan, M. S. (1992). Uvigerina proboscidea abundances and paleoceanography of the northern Indian Ocean DSDP Site 214 during the Late Neogene. *Marine Micropaleontology*, *19* (4), 355-367.
21. Gupta, A. K., & Thomas, E. (2003). Initiation of Northern Hemisphere glaciation and strengthening of the northeast Indian monsoon: Ocean Drilling Program Site 758, eastern equatorial Indian Ocean. *Geology*, *31*(1), 47-50.
22. Gupta, A. K., Anderson, D. M., & Overpeck, J. T. (2003). Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. *Nature*, *421*(6921), 354-357.
23. Hays, J. D., Imbrie, J., & Shackleton, N. J. (1976). Variations in the Earth's Orbit: Pacemaker of the Ice Ages: For 500,000 years, major climatic changes have followed variations in obliquity and precession. *science*, *194*(4270), 1121-1132.
24. King, A. L., & Howard, W. R. (2005). δ18O seasonality of planktonic foraminifera from Southern Ocean sediment traps: Latitudinal gradients and implications for paleoclimate reconstructions. *Marine*

Micropaleontology, *56*(1-2), 1-24.

25. Kotlia, B. S., Ahmad, S. M., Zhao, J. X., Raza, W., Collerson, K. D., Joshi, L. M., & Sanwal, J. (2012). Climatic fluctuations during the LIA and post-LIA in the Kumaun Lesser Himalaya, India: evidence from a 400 y old stalagmite record. *Quaternary International*, *263*, 129-138.
26. Kroon, D., Steens, T., & Troelstra, S. R. (1991). 13. Onset of monsoonal related upwelling in the western Arabian Sea as revealed by planktonic foraminifers1. In *Proceedings of the ocean drilling program, scientific results* (Vol. 1, pp. 257-263).
27. Kudrass, H. R., Hofmann, A., Doose, H., Emeis, K., & Erlenkeuser, H. (2001). Modulation and amplification of climatic changes in the Northern Hemisphere by the Indian summer monsoon during the past 80 ky. *Geology*, *29*(1), 63-66.
28. MacLeod, K. G., Huber, B. T., & Isaza-Londoño, C. (2005). North Atlantic warming during global cooling at the end of the Cretaceous. *Geology*, *33*(6), 437-440.
29. Overpeck, J., Anderson, D., Trumbore, S., & Prell, W. (1996). The southwest Indian Monsoon over the last 18 000 years. *Climate Dynamics*, *12*, 213-225.
30. Prell, W. L., Murray, D. W., Clemens, S. C., & Anderson, D. M. (1992). Evolution and variability of the Indian Ocean summer monsoon: evidence from the western Arabian Sea drilling program. *Washington DC American Geophysical Union Geophysical Monograph Series*, *70*, 447-469.
31. Quade, J., & Cerling, T. E. (1995). Expansion of C4 grasses in the late Miocene of northern Pakistan: evidence from stable isotopes in paleosols. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *115*(1-4), 91-116.
32. Rashid, H., Flower, B. P., Poore, R. Z., & Quinn, T. M. (2007). A∼ 25 ka Indian Ocean monsoon variability record from the Andaman Sea. *Quaternary Science Reviews*, *26*(19-21), 2586-2597.
33. Saher, M. H., Rostek, F., Jung, S. J. A., Bard, E., Schneider, R. R., Greaves, M., ... & Kroon, D. (2009). Western Arabian Sea SST during the penultimate interglacial: A comparison of U37K′ and Mg/Ca paleothermometry. *Paleoceanography*, *24*(2).
34. Saraswat, R., Nigam, R., & Correge, T. (2014). A glimpse of the Quaternary monsoon history from India and adjoining seas. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *397*, 1-6.
35. Sarkar, A., Ramesh, R., Somayajulu, B. L. K., Agnihotri, R., Jull, A. J. T., & Burr, G. S. (2000). High-resolution Holocene monsoon record from the eastern Arabian Sea. *Earth and Planetary Science Letters*, *177*(3-4), 209-218.
36. Savin, S. M., Abel, L., Barrera, E., Hodell, D., Kennett, J. P., Murphy, M., ... & Vincent, E. (1985). The evolution of Miocene surface and near-surface marine temperatures: oxygen isotopic evidence.
37. Schott, F. A., & McCreary Jr, J. P. (2001). The monsoon circulation of the Indian Ocean. *Progress in Oceanography*, *51*(1), 1-123.
38. Schulz, H., von Rad, U., Erlenkeuser, H., & von Rad, U. (1998). Correlation between the Arabian Sea and Greenland climate oscillations of the past 110,000 years. *Nature*, *393*(6680), 54-57.
39. Sellwood, B. W., & Price, G. D. (1993). Sedimentary facies as indicators of Mesozoic palaeoclimate. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *341*(1297), 225-233.
40. Sellwood, B. W., & Price, G. D. (1993). Sedimentary facies as indicators of Mesozoic palaeoclimate. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *341*(1297), 225-233.
41. Sikka, D. R., & Gadgil, S. (1980). On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon. *Monthly Weather Review*, *108*(11), 1840-1853.
42. Srinivasan, M. S., & Kennett, J. P. (1983). The oligocene-miocene boundary in the South Pacific. *Geological Society of America Bulletin*, *94*(6), 798-812.

43. Staubwasser, M., Sirocko, F., Grootes, P. M., & Segl, M. (2003). Climate change at the 4.2 ka BP termination of the Indus Valley civilization and Holocene South Asian monsoon variability. *Geophysical Research Letters*, *30*(8).
44. Thunell, R., & Sautter, L. R. (1992). Planktonic foraminiferal faunal and stable isotopic indices of upwelling: a sediment trap study in the San Pedro Basin, Southern California Bight. *Geological Society, London, Special Publications*, *64*(1), 77-91.
45. Vernekar, A. D., Zhou, J., & Shukla, J. (1995). The effect of Eurasian snow cover on the Indian monsoon. *Journal of Climate*, *8*(2), 248-266.
46. Wefer, G., Berger, W. H., Bijma, J., & Fischer, G. (1999). Clues to ocean history: a brief overview of proxies. *Use of proxies in paleoceanography: examples from the South Atlantic*, 1-68.
47. Wyrtki, K. (1973). An equatorial jet in the Indian Ocean. *Science, 181*(4096), 262-264.
48. Yadav, R. R. (2013). Tree ring–based seven-century drought records for the Western Himalayas, India. *Journal of Geophysical Research: Atmospheres*, *118*(10), 4318-4325.
49. Zachos, J. C., Shackleton, N. J., Revenaugh, J. S., Palike, H., & Flower, B. P. (2001). Climate response to orbital forcing across the Oligocene-Miocene boundary. *Science*, *292*(5515), 274-278.