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Review Article

High-Resolution Monsoon Records Since Last Glacial Maximum: A Comparison of Marine and Terrestrial Paleoarchives from South Asia

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Agricultural production and the availability of fresh water in Indian subcontinent critically depend on the monsoon rains. Therefore it is vital to understand the causal mechanisms underlying the observed changes in the Indian monsoon in the past. Paleomonsoon reconstructions show that the water discharge from the Ganges-Brahmaputra River system to the Bay of Bengal was maximum in the early to mid-Holocene; data from the Western Arabian Sea and Omanian speleothems indicate declining monsoon winds during the Holocene, whereas records from the South West Monsoon (SWM) precipitation dominated eastern Arabian Sea show higher runoff from the Western Ghats indicating gradually increasing monsoon precipitation during the Holocene. Thus there exists considerable spatial variability in the monsoon in addition to the temporal variability that needs to be assessed systematically. Here we discuss the available high resolution marine and terrestrial paleomonsoon records such as speleothems and pollen records of the SWM from important climatic regimes such as Western Arabian Sea, Eastern Arabian Sea, Bay of Bengal to assess what we have learnt from the past and what can be said about the future of water resources of the subcontinent in the context of the observed changes.

1. Introduction

The Indian economy is based on agriculture, which mostly depends on the monsoon rain and to some extent on river flow and ground water resources. In the absence of monsoon that brings adequate rain, crop yield is reduced and due to recurrent droughts there may even be severe shortage of drinking water. The water resources of India comprise rivers, lakes, and ground water aquifers and the amount of water they hold is linked to the rainfall on the one hand and human exploitation on the other. Thus it is important to have a correct long-term forecast of the monsoon that can help in the proper management of our water resources [1]. Monsoon prediction is seriously hampered by the nonavailability of past data, which is limited to about hundred years [2]. It is very difficult to predict the monsoon without understanding its full variability. Generating quantitative paleomonsoon data using available, dateable, natural archives, such as deep sea and lake sediments, varved sediments, and speleothems is a starting point towards this end [3–6].

Monsoon is a term derived from an Arabic word "*Mausim*" meaning weather. It is technically applied to the seasonal reversal of winds in the Indian subcontinent and Africa, especially in the Arabian Sea, due to land-sea thermal and pressure contrast. It is mainly due to coupled heating and cooling of Himalaya (Tibetan plateau) and the southern Indian Ocean and the consequent movement of the ITCZ [7]. The Asian monsoon system is a dynamic component of the modern climate system and changes in this convectively active region can result in severe droughts or floods over large, densely populated regions [8]. The inherent seasonality of monsoon circulation leads to cool, dry winters and warm, wet summers over the Asian landmass. These seasonal changes in atmospheric circulation and precipitation also affect the ocean, leading to a strong seasonality in the strength and direction of ocean currents, sea-surface temperature (SST), and salinity patterns, as is observed in the Indian Ocean and the South China Sea (SCS). In specific regions, such as the Northwestern Arabian Sea, these dynamics lead to well-defined seasonal upwelling regimes in the open-ocean and near-shore environments [9]. The south Asian monsoon has been known to be stronger during warm climate (interglacial/interstadial) and weaker during cooler periods (glacial/stadial) ([10] and references therein), while the winter monsoon behaves the other way [11–13]. Thus monsoons are components of the global climate that play an important role in water resources of the Indian subcontinent.

The Southwest monsoon (SWM) occurs during June to September and the Northeast Monsoon (NEM) affects the southern parts of the Indian subcontinent during October to December [14]. AISRTS (All India Summer Monsoon Rainfall Time Series) is available from 1871 onwards [15], which has documented the last ~140 years of rainfall. If rainfall exceeds by more than 10% from the long-term average, it is called as excess rainfall year, while when it is lower by 10% or more, it is a deficient rainfall year. But to understand full variability of monsoon, which assumes added importance in view of the presently experienced global warming, we require records of monsoon during differing climatic conditions extending back to thousands of years.

2. Multiproxy Comparison of Studies from Different Regions

Evolution and variability of the Asian monsoon system are believed to respond to at least five types of large-scale climate forcing or changes in boundary conditions [49], including (i) the tectonic development of the Himalayan-Tibetan orography, in million-year time scales, (ii) changes in the atmospheric CO_2 concentration, in time scales of tens of thousand of years, (iii) changes in the Earth's orbit that result in periodic variations of seasonal solar radiation, in time scales of tens of thousands of years, (iv) changes in the extent of ice sheets (thousand years time scales), and (v) internal feedbacks within the climate system (multiple-time scales). These factors act simultaneously and over different time scales to amplify or lessen the seasonal development of continental heating/cooling, land-sea pressure gradients, latent heat transport, and moisture convergence, all of which control the strength of the monsoon circulation. We present below a comparative analysis of multiproxy studies from diverse terrestrial (speleothems—stalactites and stalagmites from Indian and Oman caves) and marine (western, northern and eastern Arabian Sea along with Bay of Bengal) realms divided into different time periods, which would help us to understand the spatiotemporal variability and complexity of the south Asian monsoon. The focus of this paper is the high-resolution records with accurate, absolute chronology since Last Glacial Maximum (~21,000 years before present)—a period which covers extensive glaciation, deglacial period witnessing rapid climatic fluctuations, and finally the Holocene (past ~11,700 years, [4]), which is a period of relatively unvarying warmth.

2.1. Monsoon and Associated Oceanographic Effects from Marine Proxies. During the summer and winter monsoons the surface oceanic circulation in the Northern Indian Ocean (Arabian Sea and Bay of Bengal) experiences changes in direction in consonance with the changing wind patterns [50, 51]. Intense upwelling occurs along the Somalian and Oman coasts with a transport of 1.5–2 Sv in the upper 50 m [52]. The typical temperature of the upwelled water is 19–24°C [53]. The reason attributed for such intense coastal upwelling is the Ekman divergence due to the flow of strong winds parallel to the coast. The central Arabian Sea exhibits a bowl-shaped mixed layer deepening under the effect of Findlater Jet wind-stress forcing and Ekman pumping [54, 55]. The cold and dry Northeast monsoon winds accompanied by the Ekman pumping cause subduction of the high salinity surface waters in the northern Arabian Sea [56, 57].

The upwelling zones along the Somalian and Oman coasts cause intense biological and geochemical changes in this region with SST falling by ~4°C as nutrient-rich deeper water surfaces that enhance the sea surface biological productivity considerably [9, 50, 58]. Weak upwelling also occurs along coastal southwest India [50, 59]. During the Northeast monsoon, minor upwelling is observed in the northeastern Arabian Sea [50]. The cold and dry NE monsoon winds cause the deepening of the mixed layer to a depth of 100–125 m due to convective mixing in the northern Arabian Sea, which leads to nutrient injection and hence high productivity during winter monsoon in this region [60, 61]. The typical productivity values for the western Arabian Sea are 2.0, 1.0, and 0.5 g C/m^2/day for the SW monsoon, NE monsoon, and the intermonsoon periods, respectively [62, 63]. Similarly for the eastern Arabian Sea the typical productivity values are 0.6, 0.3, and 0.2 g C/m^2/day for the SW monsoon, NE monsoon, and the intermonsoon periods, respectively [64]. As the moisture laden SW monsoon winds approach the Western Ghats they are forced to ascend resulting in copious precipitation and runoff into the coastal Arabian Sea, reducing the sea surface salinity considerably [21]. Denitrification takes place due to the very low concentration of oxygen in the entire Arabian Sea from 250 m to 1250 m water depths [65, 66]. This oxygen minimum zone (OMZ) is due to the high-oxygen consumption below the thermocline for the oxidation of organic matter supplied by the high overhead surface productivity. Furthermore the sluggish flow of the oxygen poor intermediate water [66, 67] along with a strong tropical thermocline (due to relatively high SST that prevents mixing of the oxygen-rich surface waters with the deeper waters) maintains the OMZ [68, 69]. Thus OMZ and denitrification are the interplay of monsoon winds and the ensuing productivity along with other climatically controlled factors such as ocean ventilation rate [40, 70–73].

Such pronounced changes in the seawater characteristics make the Arabian Sea ideal for deciphering the past changes in monsoon intensity. The surface productivity that manifests itself in many forms such as organic, calcareous, and siliceous productivity, also affects the carbon isotopic composition of the seawater, which is preserved in the calcitic

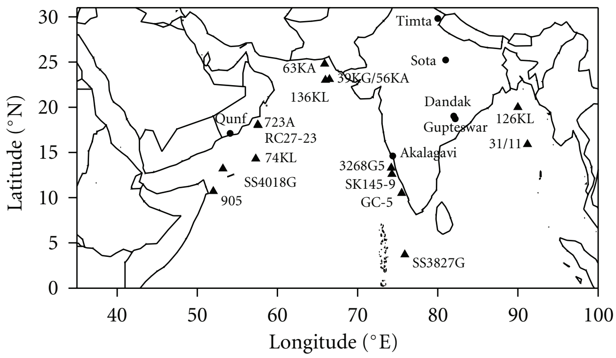

Figure 1: Sample locations discussed in the text. Triangles represent the marine-based records: 905 [78]; SS4018G [10]; 74KL [16]; RC27-23 [73]; 723A [19, 20]; 63KA [44]; 39KG/56KA [41]; 136KL [40]; 3268G5 [21]; SK145-9 [23]; GC-5 [22]; SS3827G [24]; 126KL [36]; 31/11 [37]. Circles represent terrestrial speleothem records: Qunf [32]; Akalagavi [31]; Gupteswar, Dandak [30]; Sota [86]; Timta [87].

shells of various foraminifera. Similarly the SST and sea surface salinity alter the oxygen isotopic composition of these shells and they get recorded in the sea sediments. The nitrogen isotopic composition of sedimentary organic matter can indicate the denitrification intensity relatable to productivity variations. Thus the downcore variations of such proxies could help document the past variations in monsoon intensity and the related climatic changes.

3. Discussion

Paleomonsoon studies in the Indian region were initiated around 30 years ago by Prell et al. [74] and Bryson and Swain [75]. Since then, a large number of workers ([2, 16–27, 29–32, 41–44, 76–78] and references therein) have carried out high-resolution monsoon studies in archives from various locations in and around the subcontinent that are influenced by the monsoon winds/precipitation. The data thus generated has helped document the fluctuations in the past monsoon strength both in space and time. Different proxies such as planktic/benthic foraminiferal abundances, their stable oxygen and carbon isotope ratios [18, 19, 21, 23, 24, 76, 77], varved sediments [41, 42], speleothems [2, 29–32], tree-rings [79], $\delta^{13}C$ and $\delta^{15}N$ of lacustrine and marine organic matter [10, 73, 80–83], and pollen records [84, 85] have been used to obtain paleomonsoon records with different resolutions. A few of the important proxies and their significance are shown in Table 2.

Recent marine studies have the advantage of accurate AMS (Accelerator Mass Spectrometry) ^{14}C dating, and in some case, have provided time resolutions as low as ~50 years (e.g., [23]) that can go up to subdecadal scale in extreme cases such as varved sediments [41]. The past strength of SWM was elucidated by using the above proxies from different monsoon-sensitive geographical regime (Figure 1) such as (i) the western Arabian Sea—experiences high productivity due to SWM wind induced upwelling [16–19, 76, 77]—thus record strength of monsoon *winds*; (ii) the northern

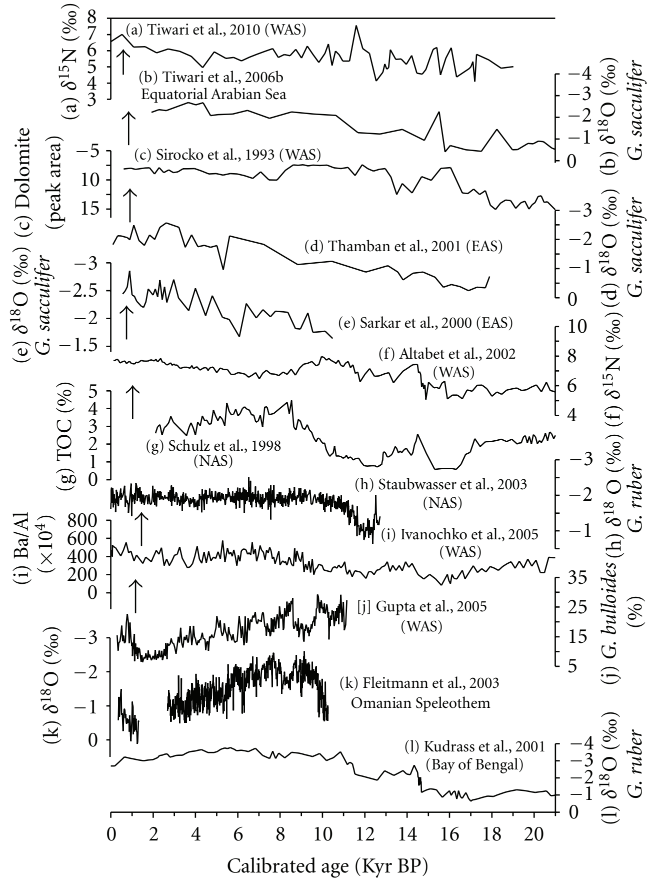

Figure 2: Variability in monsoon strength as deciphered from multiple proxies from various studies from different regions (EAS: Eastern Arabian Sea, WAS: Western Arabian Sea, NAS: Northern Arabian Sea); the arrows in each case depict increasing monsoon direction.

Arabian Sea—affected by amount of Indus river discharge [43, 44] and associated varve thickness [41, 42] relatable to SWM precipitation intensity; (iii) India and Oman—the growth rates and stable oxygen and carbon records of speleothems were used to quantitatively reconstruct SWM precipitation intensity [2, 29, 30, 32, 86]; (iv) the south-eastern Arabian Sea sediment cores which are influenced by the surface runoff due to SWM precipitation from the western Ghats of India [21, 23, 25]—thus records strength of SWM *precipitation*; (v) water discharge from the Ganga-Brahmaputra (G-B) river system into the Bay of Bengal (BOB) [35–37]. The major inferences drawn from these regions have been presented in Table 1. For Indian populace, the more important aspect of monsoon is precipitation variability that may result in severe droughts or devastating floods. Therefore it is more important to decipher this aspect for which eastern Arabian Sea is better suited than other regions of Indian Ocean. From the comparative analysis, as represented in Figure 2, among different regions, it is clear that at short-time scales, monsoon exhibits a high-spatial variability—different regions experience different trends in monsoon intensity. But when we look at multi-millennial

BP) calibrated dates	records (SWM wind records) ([10, 16–20] & references therein)	records (SWM precipitation records) [21–28]	records from India [1, 29–31]	recordsfrom Oman [32–34]	Bay of Bengal records [35–39]	Northern Arabian Sea [40–46]	World climatic records [17, 47, 48]
21000 to 15000	Weakest SWM at Last Glacial Maximum (~21 kyr BP); weak SWM during later stages of last glacial period	High $\delta^{18}O$ value of *Gs. ruber*, low productivity, that is, low C_{org} and high Pteropods abundance suggests low runoff into eastern Arabian Sea indicating reduced monsoon.	No record available		Weak SW monsoon, suggested by high $\delta^{18}O$ of *Gs. sacculifer* and *Gs. ruber* and minimum fluvial discharge observed by the high Chlorite/Illite ratio, low Kaolinite abundance.	Weak SWM based on low TOC values with minimum at ~16 kyr BP matching with Heinrich event 1.	Part of last glacial period, Synchronous with Greenland aridity
15000 to 11700	SWM strengthening commences; weaker monsoon during colder episodes such as Younger Dryas	SWM precipitation starts increasing with weaker/stronger monsoon during cooler/warmer episodes	$\delta^{18}O$ in speleothem from Timta cave, western Himalaya show fluctuating monsoon with lesser precipitation during cooler periods	No Speleothem record available	Increasingly stronger SWM suggested by low $\delta^{18}O$ of foraminifer; weaker/stronger monsoon during cooler/warmer episodes	Fluctuating monsoon inferred; weaker monsoon during cooler periods such as Younger Dryas	Deglaciation period, Synchronous with European Bolling-Allerod warm event, also coeval with melt water Pulse IA.
11700 to 10200	SW monsoon still weak as deciphered from multiple proxies	High $\delta^{18}O$ value of *Gs. ruber*, low C_{org} and high Pteropods abundance suggest low runoff	No Speleothem record available		$\delta^{18}O$ of *Gs. sacculifer* and *Gs. ruber* reduced fluvial fluxsuggested by the high C/I ratio, low Kaolinite abundance suggested the Weak SWM	Increasing monsoon observed during this period; early Holocene Monsoon maxima observed; $\delta^{18}O$ record don't show a clear-cut early Holocene monsoon maxima	End of Younger Dryas & beginning of Holocene
10200 to 9800	Multiple proxiessuggest strong SWM early Holocene monsoon maxima	$\delta^{18}O$ value foraminifera do not show a clear-cut early Holocene monsoon maxima but suggest a slightly increasing trend during that period		Low $\delta^{18}O$ value of the speleothem suggests high rainfall	$\delta^{18}O$ value of warm mixed dweller planktic foraminifera do not show a clear-cut early Holocene monsoon maxima but suggest a slightly increasing trend during that period similar to Eastern AS records		Early Holocene monsoon maxima matches with warm north Atlantic climate (low haematite in sediment cores)

BP) calibrated dates	records (SWM wind records) ([10, 16–20] & references therein)	records (SWM precipitation records) [21–28]	records from India [1, 29–31]	recordsfrom Oman [32–34]	Bay of Bengal records [35–39]	Northern Arabian Sea [40–46]	World climatic records [17, 47, 48]
9800–8800	SWM weakened after early Holocene monsoon maxima	δ^{18}O value of *Gs. ruber* suggest low runoff	No Speleothem record available	Positive excursion in the value of δ^{18}O of stalagmite suggests arid climate	Decreasing trend in the value of δ^{18}O of *Gs. sacculifer* and *Gs. ruber* suggest higher runoff	From early to mid-Holocene, the Total Organic Carbon values in the core 111KL stays more or less uniform indicating unvarying monsoon, while the δ^{18}O from nearby cores either stay unvarying or display a negative excursion indicating strengthening monsoon	Very high percentage of hematite from N. Atlantic suggests cool period
8800–5400	Up to mid-Holocene, SWM was strong based on multiple proxies although % *Gs. bulloides* exhibit a declining trend	low δ^{18}O value of *Gr. menardii* reported and suggesting high rainfall	No Speleothem record available	Increasing value of δ^{18}O of stalagmite suggest increasingly arid climate at the Oman Site	Maximum fluvial discharge suggested by low δ^{18}O and strong SW monsoon.		Low percentage of hematite from N. Atlantic suggests warm period; temperature reconstruction from Greenland Ice cores (GISP2) suggest warm climate; 8.2 kyr cool event from GISP2 is not reflected in monsoon reduction
5400–2900	During Mid-Holocene to early part of late Holocene, multiple studies show slightly increasing monsoon but a few also observed a decline (e.g., % *Gs. bulloides*)	High rain fall suggested by the lower value of δ^{18}O *Gs. sacculifer* and *Gs. ruber*	No Speleothem record availablefrom India	Increasing trend in δ^{18}O value was observed in the Oman stalagmite suggesting decreasing SWM	High water discharged by G-B river suggested by lower values of δ^{18}O *Gs. ruber*. More negative values of δ^{18}O of *Gs. sacculifer* and *Gs. ruber* suggest the higher runoff	After mid-Holocene, the TOC values decreases of *Gs. ruber* indicating declining monsoon while proxies like δ^{18}O, Ba/Al suggest an unvarying or strengthening monsoon	Low percentage of hematite at N. Atlantic suggests the humid, warm climate; GISP2 suggests continuous, unvarying warmth
2900–2100	Declining SWM deciphered from several studies	Positive δ^{18}O values of *Gs. ruber* suggest low runoff.	High-resolution speleothem records available from India; declining SWM suggested by increasingly positive δ^{18}O of Gupteswar and Sota speleothem records	No growth of Oman Stalagmite	High Chlorite content and δ^{18}O higher value suggest the arid climate	High runoff from Indus river suggested by thicker varve sediment layer	GISP2 temperature records suggest unvarying northern hemisphere, high-latitude warmth

Time periods (yr BP) calibrated dates	Western Arabian Sea records (SWM wind records) ([10, 16–20] & references therein)	Southeastern Arabian Sea records (SWM precipitation records) [21–28]	Speleothems records from India [1, 29–31]	Speleothem recordsfrom Oman [32–34]	Bay of Bengal records [35–39]	Northern Arabian Sea [40–46]	World climatic records [17, 47, 48]
2100–1900	A period of widespread aridity is reported from varied regions & proxies such as $\delta^{18}O$ of foraminifera, abundance (~5%) of *Globigerina bulloides* and reduction in dinoflagellate population in the west Arabian sea suggesting weak upwelling, weak SWM	Positive $\delta^{18}O$ values of foraminifera suggest low freshwater run-off indicating severely weakened SWM precipitation.	Extremely low rain fall recorded from Gupteswar stalactite, suggested by the prominent positive excursion in $\delta^{18}O$ values	No growth of Oman Stalagmite	Low Chlorite ratio, high Kaolinite ratio and depletion in $\delta^{18}O$ of *Gs. ruber* suggests the arid climate andreduced water discharge in to BOB	Positive values of $\delta^{18}O$ & reduced varve thickness indicate reduced Indus river discharge	Low percentage of hematite at N. Atlantic suggests humid, warm climate
1900–1600	Slightly strengthening monsoon but overall the monsoon is on weaker side	$\delta^{18}O$ records of *Gs. ruber* and *Gs. sacculifer* suggest increasing SWM	Lower $\delta^{18}O$ record from both Gupteswar & Sota caves suggest increasing trend of rainfall.	No growth of Oman Stalagmite	Slight positive excursion observed in the foraminiferal $\delta^{18}O$ values indicating declining monsoon	An increase in the thickness of varve sediment suggests the higher water discharge from Indus	Higher hematite content suggest cold climate in N. Atlantic
1500–1400	Very low abundance of *Globigerina bulloides* (5%) suggests extreme reduction in upwelling and wind strength	Higher value of $\delta^{18}O$ records of *Gs. ruber* and *Gs. sacculifer* suggest weakening of SWM	High $\delta^{18}O$ of Gupteswar stalactite, Orissa suggests the weak monsoonal run-off	No growth of Oman Stalagmite	Slightly declining trend in $\delta^{18}O$ values of foraminifera indicate strengthening monsoon	An increase in the thickness of varved sediments suggests higher water discharge from Indus	Low value of Hematite percentage at North Atlantic (Medieval warm period)
1400–1200	Multiple proxies suggest increasing monsoon during this period	A clear-cut decreasing trend in foraminiferal $\delta^{18}O$ values indicate strengthening monsoon	Depletion in $\delta^{18}O$ shows increasing trend of rainfall recorded at Gupteswar and Dandak caves.	High precipitation indicated by Oman stalagmite depleted $\delta^{18}O$ record			

1200–1000	abundance & other proxies suggest significantly weak upwelling due to weakened SWM	An arid event centered at ~1100 yr BP reflected by the sudden decline in δ^{18}O of *Gs. ruber* and *Gs. sacculifer*	Low rain fall recorded at Gupteswar and Dandak caves	Higher δ^{18}O values suggest arid conditions		Lower varve thickness and high δ^{18}O of *Gs. ruber* suggests weak SWM (63 KA)	Low value of Hematite percentage at North Atlantic (Medieval warm period)
1000–800	Very low abundance of *Globigerina bulloides* suggests the weak SWM	Increase in δ^{18}O records *Gs. ruber* and *Gs. sacculifer* of due to increase in salinity of east Arabian Sea suggests major event of aridity centered at ~850 yr BP	Aridity observed at Dandak caves indication reduced precipitation	Oman stalagmite records the increase in δ^{18}O which suggest an arid condition		Lower Varve thickness and sharp increase in δ^{18}O of *Gs. ruber* suggests the weak SWM	
800–500	Decreasing trend of *Gg. bulloides* abundance suggests weak SWM	Low runoff, reduced precipitation event centered at ~500 yr BP suggested by increase in δ^{18}O of *Gs. ruber* and *Gs. sacculifer*	Depletion in δ^{18}O shows increasing trend of rainfall recorded in Gupteswar & Dandak speleothem	Negative excursion in speleothem δ^{18}O values indicate strengthened precipitation	After a slight peak, the δ^{18}O exhibit positive excursion indicating reduced SWM strength	Lower varve thickness suggests weak monsoon strength	Increasing trend in the % of hematite at N.Atlantic suggests the cool climate
500–400	High abundance of *Gg. bulloides* suggests strong SWM	Increase in the δ^{18}O records of *Gs. ruber* and *Gs. sacculifer* suggest weak SWM	Reduced precipitation suggested by increase in δ^{18}O speleothems record	Reduced precipitation suggested by increase in δ^{18}O record in Oman stalagmite		Lower Varve thickness and high δ^{18}O of *Gs. ruber* suggests weak SWM	Synchronous with little Ice Age, cooling at Bermuda rise and brief increase in hematite percentage
400–300	Very low abundance of *Globigerina bulloides* suggests weak SWM		High rain fall inferred from Dandak, and Gupteswar caves		Ganges-Brahmaputra river discharge shows a declining trend		
300–100	High abundance of *Gg. bulloides* suggests the strong SWM	SWM shows an increasing trend	Rain fall increased as seen in from Dandak Gupteswar Sota and Akalagavi caves, the lower δ^{18}O record suggests higher runoff	No growth of Oman Stalagmite		High varve thickness off Karachi and low δ^{18}O of *Gs. ruber* suggest strong SWM	Low value of Hematite percentage at North Atlantic indicating warm, humid climate
50–Present	High abundance of *Gg. bulloides* suggest strong SWM		Very low rain fall was recorded from Dandak and Akalagavi caves				

TABLE 2: A few of the important proxies/archives used for monsoon reconstruction and their significance.

S. No.	Proxies/archives discussed in the present work	Significances of each proxies
(1)	Oxygen isotopes of Speleothems and Foraminifera	Oxygen isotopes of foraminifera reflect the isotopic composition of the seawater that depends on salinity and temperature. Eastern Arabian Sea receives abundant fresh water as either direct precipitation or runoff from the adjacent Western Ghats during the Southwest monsoon. This reduces the sea surface salinity (SSS) that is reflected in negative excursion in the oxygen isotopic composition of planktic foraminifera.
(2)	*Globigerina bulloides* abundance in tropical oceans	The spatial distribution of *Globigerina bulloides* in the world ocean shows that it is dominant in temperate subpolar water mass and thus the only likely cause for high abundance in low latitude areas (tropical oceans) has been upwelling induced productivity. The initiation of upwelling in the western Arabian Sea and the subsequent increase in *Globigerina bulloides* flux indicates that foraminiferal population respond within a few weeks to changes in near surface hydrography, which has been demonstrated in studies from Western Arabian Sea Sediment Trap data. The enhanced upwelling in the Arabian Sea, especially western region, is strongly correlated to Southwest monsoon.
(3)	Carbon isotopes of foraminifera	Kinetic isotope effects during photosynthesis cause preferential uptake of ^{12}C in the organic matter, which enriches the ambient dissolved bicarbonate in heavier isotopes (^{13}C). The foraminifera secreting calcareous shells in equilibrium with the ambient water will record these isotopic signatures. Thus a higher $\delta^{13}C$ value probably corresponds to an enhanced rate of photosynthesis in the euphotic layer that indicates an increase in productivity relatable to stronger monsoon.
(4)	Nitrogen Isotopes of sedimentary Organic matter	Due to lack of oxygen in Oxygen Minima Zone, the anaerobic bacteria utilize NO_3^- for the decomposition of organic matter. During this process they preferentially consume NO_3^- with lighter isotope (^{14}N), thus enriching the residual nitrate in the heavier isotope, which gets upwelled to the sea surface and is taken by the organisms as a nutrient. This enriched nitrogen isotopic signature is preserved even when the organic matter settles down and gets preserved in sea sediments. Thus a high $\delta^{15}N$ can be related to increased denitrification, which in turn is controlled by the productivity increase relatable to monsoon strength.
(5)	Total Organic Carbon & Inorganic Carbon	Total Organic Carbon (TOC) preserved in the sea sediments is derived from the particulate organic carbon (POC, the carbon content of particulate organic matter) and is a manifestation of the overhead primary productivity if there are no alterations after the deposition. The overhead rain of calcitic shells is a major constituent of the sea sediments. It has been observed that during the monsoon season in the Arabian Sea, 50–60% of the total flux to the bottom is composed of calcitic material. Thus calcium carbonate percentage in the sea sediments can indicate the overhead productivity provided the core has been raised from depths above the lysocline (~3800 m in the Arabian Sea) and there is no contamination from the terrigenous inputs

time scales then we find that monsoon records from varied realms exhibit similar trends.

Fleitmann et al. [32] deciphered declining SWM precipitation during the Holocene based on speleothems from Oman. But this region is near the edge of the monsoon precipitation and receives very little rain as compared to the Indian subcontinent. Moreover, such arid/semiarid regions with dynamic karstic terrains have been reported to have long residence time of water up to decades [88]. Also, the strong evaporation in such regions could greatly alter the $\delta^{18}O$ of precipitation during infiltration and in the upper portion of the vadose zone [89], making such reconstructions somewhat ambiguous. In the western Arabian Sea during the Holocene, a few of the SWM wind intensity, based proxies (e.g., content of *G. bulloides*—a calcareous micro-organism flourishing in the cooler, upwelled waters during SWM season) showed that monsoon winds have been declining, following the reduction in insolation. On the other hand, studies from the eastern Arabian Sea, which record SWM precipitation, have indicated otherwise. The eastern Arabian Sea receives abundant fresh water as either direct precipitation or runoff from the adjacent Western Ghats (*Sahyadri* Hills) that induces intense orographic precipitation during the SW monsoon. This reduces the sea surface salinity (SSS) that is reflected in the oxygen isotopic composition ($\delta^{18}O$) of planktic foraminifera. Such reconstructions have indicated increasing strength of SWM precipitation during the Holocene [21, 22, 27]. Similarly, Agnihotri et al. [28] have found increasing productivity during the Holocene based on denitrification intensity

($\delta^{15}N$), which is relatable to SWM strength. To resolve this apparent contradiction between the studies from the western and the eastern margins of the Arabian Sea, Tiwari et al. [10] studied productivity proxies from the western Arabian Sea. They found out that the reason for declining trend observed in the planktic carbonate production (relative abundance (%) of *G. bulloides*—[19] and declining %$CaCO_3$—[10]) is the preference to silicate productivity over calcareous productivity during periods of enhanced monsoon winds. During initial stages of SWM (weaker monsoon winds), upwelling takes place from shallower regions bringing nitrate and phosphate to the surface that supports calcareous microorganisms. But as the monsoon progresses and the winds became stronger, upwelling takes place from the deeper waters, injecting silicate to the photic zone, which enhances siliceous productivity [90, 91]. This has been observed in sediment records of past climate as well [45, 92]. Other productivity indicators (organic carbon, $\delta^{15}N$, $\delta^{13}C$ of three species of foraminifera) analyzed by Tiwari et al. [10] unambiguously indicate strengthening monsoon during Holocene, unlike insolation that declines during the same period. This multiproxy result indicates that, on sub-Milankovitch, multi-millennial timescales, monsoon is predominantly governed by internal feedback mechanisms and lagged summer insolation maxima by several thousand years, as noted earlier by Clemens et al. [49].

4. Conclusions

In essence, the above discussion shows that there exists a large spatial variability in monsoon records, which becomes more pronounced on shorter timescales. But on longer time scales, a more coherent picture emerges. On glacial-interglacial time scales, SWM was stronger (weaker) during the warmer (colder) periods, with a minimum during the Last Glacial Maximum. During deglaciation, monsoon fluctuated widely with weaker monsoons during colder episodes such as Younger Dryas and stronger monsoons during warm episodes such as Bølling-Allerød. During the early Holocene, a widely reported SWM maximum is followed by a decline. Thereafter, during the Holocene, the SWM either stayed uniform or showed decline only after the mid-Holocene, which needs to be verified further with accurately dated records from both the western and eastern Arabian Sea margins. During the Holocene, monsoon did not decline following the reducing insolation, which highlights the importance of internal feedback mechanisms. On short time scales (millennial to subcentennial), a period of widespread aridity is reported at ~2000 yr BP followed by arid periods at ~1500 yr BP, ~1100 yr BP, ~850 yr BP, and ~500 yr BP [23]. On such short time scales (centennial to subcentennial), monsoon has been reported to follow insolation [93]. This highlights complex dynamics of SWM at different timescales. This intercomparison of monsoon records from different regions show that despite the considerable spatial variability in monsoon strength, it increases during warmer periods in general. This indicates that monsoon may strengthen in the future scenario of global warming that corroborates the model results represented in IPCC AR4. An understanding of this requires systematic studies covering various regions under the SWM realm using multiple proxies at different spatiotemporal scales.

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