Tracking Indian monsoon variability from changes in sediment provenance

Neeraj Awasthi[1,]* and Jyotiranjan S. Ray[2]

[1]Department of Earth and Planetary Sciences, Prof. Rajendra Singh (Rajju Bhaiya) Institute of Physical Sciences for Study and Research, VBS Purvanchal University, Jaunpur 222 003, India
[2]Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India

Terrestrial and marine sediments preserved on the Indian sub-continent and in seas/oceans around it are excellent archives for studying and reconstructing past variations in monsoonal climate. Based on the multiproxy studies on the sediment cores, a coherent relationship between the intensities of the monsoon and glacial–interglacial conditions and a strong atmospheric teleconnection between the Asian and North Atlantic climates has been suggested. Terrestrial sediment cores clearly established that the variations in the monsoonal climate and/or change in glacial extant played an important role in varying weathering/erosion in source regions and relative supply of sediments. Marine sediment studies presented a more complicated picture because their depositions were influenced by changes in sea-levels, movement of shorelines, river mouths, deltas and sea surface-circulations. A composite climate record suggested that the intensity of Indian SW monsoon has weakened and NE monsoon strengthened during glacial periods and vice-versa during the interglacial periods.

Keywords: Climate, Himalaya, Indian monsoon, sediment cores, Sr–Nd isotopes, weathering-erosion.

Introduction

THE Indian monsoon system is one of the most important weather systems on the Earth[1,2]. The monsoonal rains are looked forward to with great anticipation and have widespread socio-economic impacts on the large populations inhabiting the South and Southeast Asian countries[3]. By controlling food and agricultural production and growth of regional flora and fauna, it largely controls the life of people living in these regions. The Indian subcontinent experiences two monsoons annually, the south–west (SW) or summer monsoon and the north–east (NE) or winter monsoon (Figure 1). These monsoons bring rainfall by picking up the moisture during seasonal reversals of the wind directions along the shore of the Indian Ocean especially in the Arabian Sea and surrounding regions.

Several studies have emphasized that the monsoonal changes played an important role in the origin, evolution and dispersal of mankind not only in the present times, but also during the geological past[4–6]. However, it has been always difficult to accurately understand, evaluate and reconstruct the climate variability records for longer time scales of several thousand or million years, for which we have to rely on a variety of physical and chemical proxies available both over the lands as well as in the oceans[7]. Constant efforts have been made in past few decades to refine the available records and reconstruct the variability of the monsoon on longer time scales through analyses of various physical and chemical parameters like distribution of grain size, clay minerals, heavy minerals, mineral magnetism, phytoliths, palynology, diatoms, major and trace elements and isotope ratios (of C, O, N, Sr and Nd) in ice cores, detrital sediments, organic and inorganic matter on sedimentary archives like sediments in lakes and ocean, peat bogs, loess, and speleothems[3]. Thus, the continental and marine sediment records have proven to be consistent proxies for reconstructing millennial scale palaeoclimate variability records; despite that considerable discrepancies still exist in analytical precision and resolution.

The available records of monsoonal patterns based on the studies of atmospheric CO_2, Asian speleothems and cores from the Arabian Sea, uniformly indicate centennial to millennial scale variations in the intensities of the Indian monsoon in tune with the changes in glacial and interglacial conditions[8–11]. These studies have demonstrated that the low latitude solar insolation, driven by precession and eccentricity of the Earth's orbit around the Sun have largely controlled these intensities of monsoon at least since the last 1 myr (refs 12–14). Several of these studies, emphasized that the NE monsoon strengthened during the glacial periods and were closely associated with the contemporaneous changes recorded in the Greenland ice cores and cold Heinrich events recognized in the North Atlantic during the last glacial cycle[14,15]. In contrast, during the interglacial periods the SW monsoon was stronger coinciding with the Dansgaard–Oescher (DO) events. Strong NE monsoon was also recognized during the cold event of Younger Dryas (YD) whereas strong SW monsoon was witnessed during the warm Bølling–Allerød (B–A) period[14,16].

*For correspondence. (e-mail: aneeraj.geology@gmail.com)

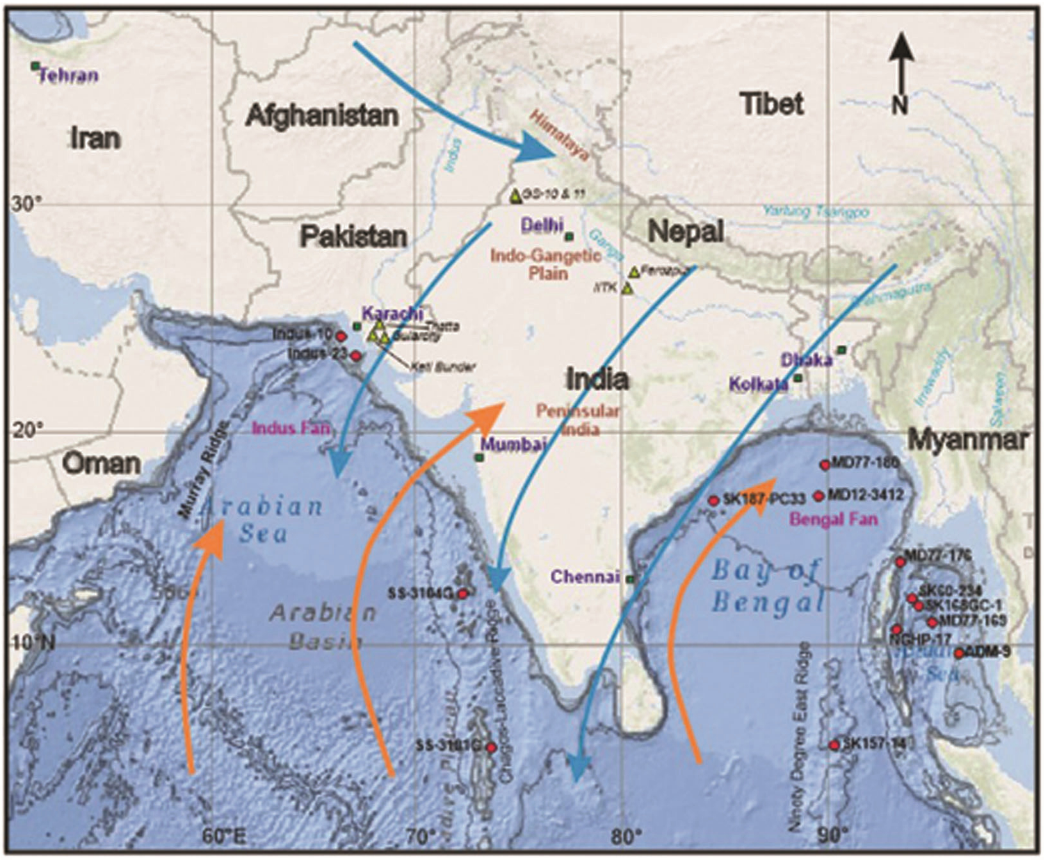

Figure 1. Map of South Asia showing locations of marine (circle) and terrestrial (triangle) sediment cores studied for the monsoon variability based on changes in sediment provenances. The orange arrows show directions of SW or summer monsoon winds whereas blue denotes directions of NE or winter monsoon winds. Base map source: https://maps.ngdc.noaa.gov/viewers/bathymetry/.

The Holocene period, which started at ~11.5 ka, is characterized by relatively warmer conditions and a marine transgression that resulted in major shift of the coastlines throughout the world. The speleothem records from various caves throughout the Asia and sediment cores from the Arabian Sea showed that the northern hemisphere temperatures and monsoon peaked between ~10.4 and 5.5 ka during the so called 'Holocene climatic optimum'[16–18]. A wealth of proxy data strongly suggested that a major northward expansion of monsoonal rain occurred during this period[19]. An abrupt cooling peak and weakening of the SW monsoon at ~8.2 ka interrupted the Holocene climatic optimum condition[20,21]. After ~5.5 ka, consecutive shifts were noted in northern Africa and Asia towards drier conditions with a persistent record of drought at ~4.2 ka due to the aridification[22,23]. Overall, the intensity of the monsoon oscillated with millennial scale frequency throughout the Holocene.

The consistent record of major climate transitions as shown by various proxies during the B–A, the YD, and the Holocene suggested these events affected a large area of the monsoon region more or less in the same way and to the same degree[24]. On the Indian sub-continent, studies have shown that these millennial scale variations in the monsoonal intensities and patterns during the past have also significantly affected the chemical and/or physical weathering of drainage basins within the Himalaya, peninsular India region and Indo–Burman (I–B) ranges[25,26]. This consequently influenced the fluvial sediment discharge to the plains and to the seas around the Indian subcontinent (Andaman Sea, Bay of Bengal and Arabian Sea)[27]. Such climatic variations, combined with fluctuations of sea-level have repetitively exposed and submerged large portions of the shelves in the Bay of Bengal, Andaman and Arabian Seas[28–30] and also influenced sea–water circulation patterns responsible for dispersal and deposition of sediments in the Indian Ocean[31–34].

As continental and marine sediments are well-preserved in the alluvial plains and seas around India, these have been excellent archives for studying and establishing links between erosion and climate (monsoonal intensity) change[33,35,36]. Studies from marine sediment cores spanning last glacial–interglacial interval have clearly demonstrated that these sedimentary archives provide the most reliable and continuous record of the monsoonal variability. This work presents a review highlighting the past variabilities observed in the intensity of the monsoon as shown by change in sediment provenance. For this, we have presented and discussed results from terrestrial and marine sedimentary records from the Indian subcontinent and surrounding ocean. The periods of maximum and minimum moisture availability have been well studied in the southern Asian region using $\delta^{18}O$ of cave stalagmites form various locations[37,38] and other stable isotope proxies (δD) from the northern Bay of Bengal[39]. By comparing the marine and terrestrial records, we discuss the evidences for the long and short-term events. For convenience, we have discussed these works and findings under two headings: (a) continental palaeoclimatic records and (b) marine palaeoclimatic records. We restricted our comparison of the results for last 100 ka, for which most reliable data is available in the literature. Although the results discussed in these works are supported by multiple proxies, we limited our discussion to the Sr and Nd isotope compositions ($^{143}Nd/^{144}Nd$, generally represented by ε_{Nd} parameter which is given by the formula

$$\varepsilon_{Nd(0)} = \{[(^{143}Nd/^{144}Nd)_S - (^{143}Nd/^{144}Nd)_{CHUR}]/ (^{143}Nd/^{144}Nd)_{CHUR}\} \times 10^4,$$

where subscript *s* stands for sample and 'CHUR' stands for Chondrite Uniform Reservoir which has present day value of 0.512638) of the detrital fractions in sediment cores. Nd isotope ratios are well-established and powerful tracers for sediment sources that have been used since long time to understand the origin of sediments and the mechanisms responsible for particle transport[40–43]. These ratios are unlikely to be significantly modified during chemical weathering processes on land and resistant to grain-size sorting during transport[43,44]. Although provenance studies of marine sediments based on Nd isotope have some limitations of application due to their long residence time in floodplains, the cores studied here are free from such limitations because most of them are from the deeper parts of sea with clay to silt size grain fractions. Based on U–Th studies on sediments, it has been found that the fine-grained sediments have much shorter transfer time (a few ky or less) than for the coarse-grained sediments (100 ky or more)[45]. Therefore, these sediments reflect true signals of changes in source compositions, climate and other oceanographic processes. Sr isotope compositions are less reliable for provenance studies because these are easily influenced by weathering processes and grain-size sorting affects during transport[45,46] despite this, in many publications these have been used in conjunction with Nd isotopes to understand the provenance of sediments.

Continental palaeoclimate records

A number of studies have emphasized that provenance signatures are better preserved in the continental sediments compared to marine sediments[33,34,26]. Therefore, sometimes continental sediments are preferred over the marine sediments for studying variations in sediment provenance and/or climate because being close to the sources, the sediments on lands respond faster to the cause of variations in sediment provenances as well as provide better time resolution[28]. If we look at the continental records of palaeoclimate based on provenance of sediments, we are geographically restricted to Indo-Gangetic Plains which have relatively well-preserved thick sequences of sediments of Quaternary period (Figure 1). Because of this, several deep sediment cores have been recovered from this region. The Indo-Gangetic Plains are bordered by the Himalaya in the north and peninsular India in the south and combinedly cover a total area of around 2.5 million sq. km (Figure 1). It acts as a transient storage space for huge amount of sediments derived from both the Himalayan and peninsular India sources that are carried by numerous rivers originating from them and finally funnelled into the Bay of Bengal or the Arabian Sea. The Indo-Gangetic Plains are dominantly affected by the SW monsoons. However, these also get sufficient non-monsoonal precipitation driven by the westerlies known as 'Western disturbances', specifically during winters that bring moisture from Central Asia and Mediterranean[47]. Some of the cores recovered from the Indo-Gangetic Plains have been discussed below, the detail sampling information for which is provided in Table 1. Table 2 shows Sr and Nd isotope compositions of the potential source regions contributing sediments to the Indo-Gangetic Plains. $^{87}Sr/^{86}Sr$ and ε_{Nd} compositions of these cores with their sources are plotted in Figure 2 *a*.

Ganga Plain

Core IITK

A 50 m-long sediment core was studied from the Ganga-Yamuna Interfluve (~14 km south of the Ganga) in the Indian Institute of Technology, Kanpur campus to understand relationship between the varying climate (monsoon and/or glaciation) and erosion of the Himalaya over millennial year time scales (Figure 1). The chronology of the core was established based on ^{14}C dating of the carbonate nodules and luminescence dating on etched K-feldspar that gave ~100 ka depositional record of floodplain without any major break[48] (Figure 3). Based on the Sr and Nd isotope compositions of sediments collected along the course of the Ganga river and its major tributaries, and sources in the Higher Himalaya (HH) and Lesser Himalaya (LH)[49], it was hypothesized that these were the only sources to the sediments at IITK core site essentially brought by the River Ganga.

$^{87}Sr/^{86}Sr$ and ε_{Nd} variations along the entire length of the core suggested input of sediments from the HH and LH sources varied with time. The erosion and proportional mixing of sediments from both the sources depended

Table 1. Locations and sampling depths of the sediment cores studied from the Indo-Gangetic plain, Andaman Sea, Bay of Bengal and Arabian Sea

Core	Location	Length (m)	Water depth (m)	Reference
Indo-Gangetic plain			–	
IITK	26°30′50″N, 80°14′00″E	50	–	26
Firozpur		25	–	51
GS-10	29°28′14″N, 74°07′49″E	45	–	81
GS-11	29°28′14″N, 74°07′49″E	45	–	81
Keti Bundar	24°8′35″N, 67°27′3″E	120.8	–	25
Andaman Sea				
MD77-176	14°30′05″N, 93°07′6″E	9.5	1375	55
MD77-169	10°12′05″N, 95°03′0″E	14.4	2360	55
SK-234-60	12°05′46″N, 94°°05′18″E	4	2000	54
SK168/GC01	11°42′00″N, 94°29′0″E	4.2	2064	56
NGHP-17	10°45.19′N, 93°6.74′E	700	1356	57
ADM-9	9′33′32″N, 96°04′9″E	2.7	1242	58
Bay of Bengal				
MD77-180	18°28′03″N, 89°51′04″E	10.1	1986	64
MD12-3412	17°10′94″N, 89°28′92″E	32.2	2368	64
SK-157-14	5°12′00″N, 90°06′00″E	2	3306	32
SK-187-PC33	16°16′00″N, 84°30′00″E	12.8	3003	34
Arabian Sea				
Indus-10A-P	24°29.05′N, 66°33.96′E	9	70	30
Indus-23A-P	23°36.656′N, 67°16.307′E	7.7	70	30
SS-3104G	12.8°N, 71.7°E	1.35	1680	71
SS-3101G	6.0°N, 74.0°E	1.52	2680	71

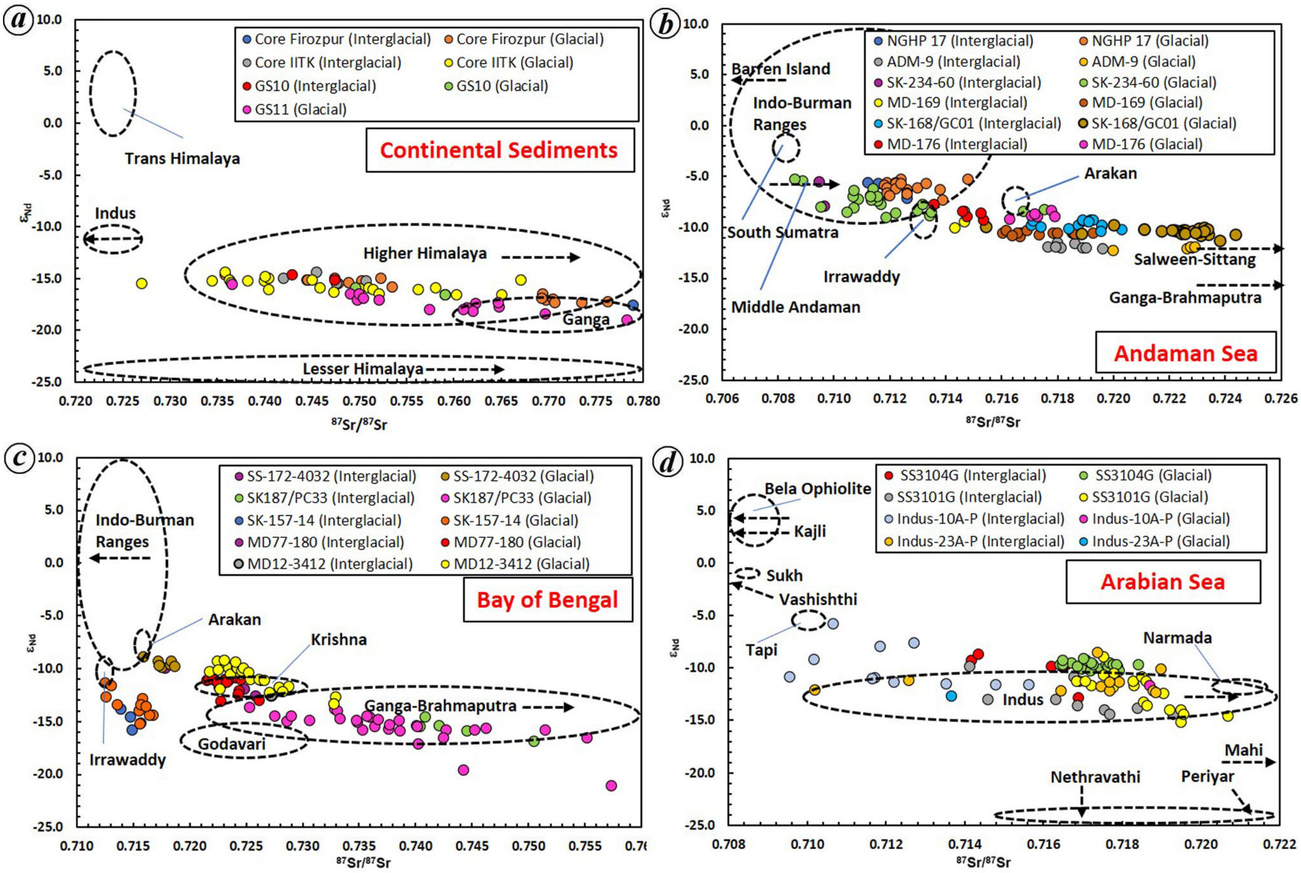

Figure 2. Plot of $^{87}Sr/^{86}Sr$ and ε_{Nd} compositions of studied cores with their sources: ***a***, Continental sediments, ***b***, Andaman Sea, ***c***, Bay of Bengal; ***d***, Arabian Sea.

Table 2. Typical Sr and Nd isotope compositions (signatures) of potential source regions used by various authors considered in this work

Sources	$^{87}Sr/^{86}Sr$	ε_{Nd}	Reference
Trans-Himalaya		–1 to +8	25
Higher Himalaya	0.76 ± 03	–15 ± 1.4	26, 51, 81, 34
	0.73 to 0.84	–20 to –10	33, 55
		–17 to –12	25
Lesser Himalaya	0.715 ± 0.003		26
	0.85 ± 0.09	–2 ± 0.9	34, 51, 81
		–26 to –23	25
	>0.84	–26 to –24	33, 55
Barren Island	0.703	+5.2	57
Middle Andaman		–5.1 to –5.2	57
South Sumatra	0.70850	–2.8	58
Bela Ophiolite	0.70421–0.70603	+2.86 to +6.11	30
Indo-Burman Ranges	0.713	–10	34
	0.703–0.710	–4 to +12	54
	0.715	–9	32
Arakan	0.716	–7	34, 64
		–8.88 ± 0.33	56
Irrawaddy	0.71333	–10.7	33, 55, 58, 57, 56, 53, 32
		–8.72 ± 0.33	56
Salween	0.732	–10.37 ± 0.33	56
Sittang		–11.19 ± 0.33	56
Ganga	0.76959	–17.7	58
	0.78151	–17.2	58
	0.769–0.782	–17.7 to –17.2	64
Brahmaputra	0.73457	–16.9	58
	0.74884	–16.3	58
	0.721–0.749	–16.9 to –13.6	64
Lower Meghna	0.738–0.753	–17.4 to –14.8	64
Ganga–Brahmaputra (combined)	0.720–0.780	–16 to –13	32
		–15	57
Godavari	0.719–0.730	–18.2 to –15.3	64, 32
Krishna	0.721–0.730	–12.0 to –12.8	64, 32
Mahi	0.73051	–20.3	71
Narmada	0.72126–0.72121	–11.9 to –11.5	71
Tapi	0.70947–0.70961	–5.7 to –5.9	71
Nethravathi	0.72176–0.71507	–40.8 to –32.6	71
Periyar	0.72379–0.72176	–26.2 to –28.2	71
Kajli	0.70529	+2.2	71
Sukh	0.70885–0.70888	–1.3 to –1.2	71
Vashishthi	0.70636	–1.2	71
Indus	0.710–0.725	–11.8 to –13.5	30

on the variations in the climate (monsoon precipitation and/or glacial cover). In the studied core, two major excursions were observed in the $^{87}Sr/^{86}Sr$ and ε_{Nd} profiles (with higher $^{87}Sr/^{86}Sr$ and lower ε_{Nd}), one at ~20 ka and another at ~70 ka. Beside these, there were two minor excursions at ~40 and at ~90 ka. These excursions coincide with periods of weak SW monsoon intensity when the precipitation was minimum and source regions in HH were largely covered by glaciers. Such conditions led to decrease in the rate of erosion in the HH and consequently lowered the proportion of sediments supplied to the core site. The well-correlated records of climate and Sr and Nd isotope compositions of sediments established that the climate had great influence on Himalayan erosion over millennium time scales.

Core Firozpur

About 40 km north of the above discussed IITK site and about 25 km north of the present Ganga river, another core named Firozpur core was extracted from the palaeo-meander channel within the western Ganga Plain[48,50] (Figure 1). Optically Stimulated Luminescence (OSL)

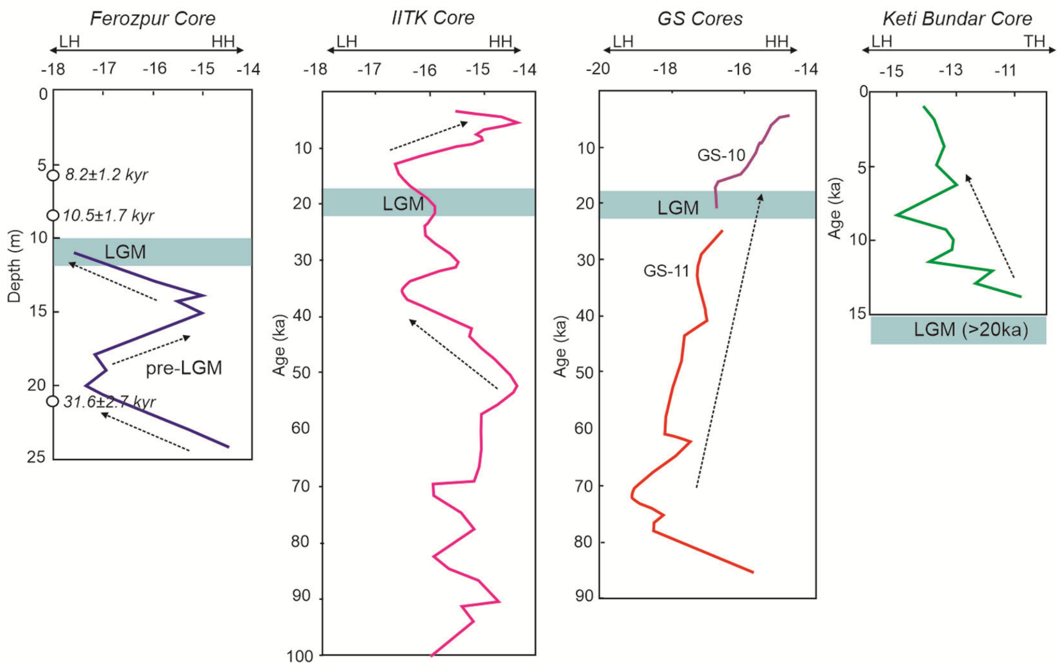

Figure 3. Comparison of ε_{Nd} variations versus depth/age in studied sediment cores recovered from the Indo-Gangetic plains. LH, HH and TH are Lesser Himalaya, Higher Himalaya and Trans-Himalaya sources respectively.

dating of this 25 m long core provided three ages, 8.5 ± 1.2, 10.5 ± 1.7 and >31.6 ± 2.7 ka at about 4.6, 7.6 and 18.5 m of depth respectively[47] (Figure 3). Based on the sedimentary facies analyses, the core represents late Quaternary valley-fill deposits of the Ganga river deposited by repeated events of valley aggradations in contrasting climatic regimes[48]. These sediments mainly consist of channel and floodplain deposits with two fining-upward cycles (cycles I and II). The cycle I began at >31.6 ka and mainly consists of sediments of floodplain facies capped by channel sand facies (~3 m thick) that graded up into very fine sand to silt and overlaid by red-brown floodplain mud facies (~9 m thick). Occasionally, carbonate nodules also occurred that were formed during the breaks in sedimentation in the Ganga Plain[48,51].Valley aggradation paused during the drier climatic conditions of last glacial maxima (LGM) when the Ganga river was in under-fit condition resulting into formation of lakes due to decrease in monsoonal rainfall and increased aeolian activity. The cycle II started during the Holocene with deposition of channel sand (~8 m thick) and is overlaid by intercalated finer sands and yellow-brown mud with a modern soil at the top.

Based on the $^{87}Sr/^{86}Sr$ and ε_{Nd} compositions of the bulk silicates of these valley-fill deposits and following the interpretations of the Singh *et al.*[49], the sediments to the core site were suggested to have been derived from the erosion of silicate rocks exposed within the HH and LH. The erosional pattern and sediment supply from the Himalaya to the Ganga Plain was largely regulated by climate changes. The $^{87}Sr/^{86}Sr$ and ε_{Nd} values at the core site showed striking change in isotope compositions suggesting these sources remained unstable during the last glacial–interglacial cycle. The valley aggradation started before ~31 ka under the humid climatic conditions. During these times, high rainfall conditions over the HH contributed higher amount of the sediments in the Ganga main stream. On the other hand, the valley aggradation ceased during LGM probably due to the reduced monsoonal rainfall. The $\delta^{18}O$ values of soil carbonates showed good correlations with Sr and Nd isotopic ratios in silicates[48]. In the core, the periods with higher monsoonal rainfalls (more negative $\delta^{18}O_{carb}$) were characterized with lower $^{87}Sr/^{86}Sr$ and high ε_{Nd} values in silicates pre-LGM at ~15 m depth suggesting more sediment from the HH. On the other hand, weak monsoonal phases (less negative $\delta^{18}O_{carb}$) characterized by high $^{87}Sr/^{86}Sr$ and low ε_{Nd} values pre-LGM at ~20 m depth and during LGM suggested relatively higher contribution from the LH and low precipitation over the HH. A rough estimation based on mixing from the two sources yielded 100% sediment contribution in the Ganga Plain from the HH pre-LGM at about 23.8 and 15 m depths and 30% sediment contribution from the LH pre-LGM at about 20 m depth and during LGM.

Indus Plain

Cores GS-10 and GS-11

With an objective to study temporal variations in sediment sources and weathering/erosion in response to glacial–interglacial changes in climate, two sediment cores (~40–45 m deep) were raised from the Ghaggar Plains of NW India close to the modern Ghaggar river channel, near the Kalibangan village in Rajasthan (Figure 1). The core GS-10 was taken from the centre of the buried channel, ~300 m southeast of the modern Ghaggar river whereas the core GS-11 was collected ~1.2 km further south of GS-10. Facies analyses showed both the cores were made of aeolian and fluvial sediments. OSL dating on the aeolian sediments provided late Quaternary ages of ~150 ka that were overlaid by layers of fluvial sediments dated to range from >71 ka to 6.4 ka and >68 ka to 7.2 ka for the cores GS-10 and GS-11 respectively (Figure 3).

Lithologically, the deeper parts of both these cores consist of coarse to medium-grained sand deposited in high energy environment. Low CIA values suggested these deeper sediments to be weakly weathered probably brought down to the core sites by a large river system originating in the Himalaya. The high energy deposits were overlaid by relatively low energy channel deposits of fine-grained sand and silt bodies followed by finer silty/clayey floodplain sediments. These low energy channel and floodplain deposits from shallow depths show intermediate weathering. The younger floodplain sediments (~12 ka) in the GS-10 core have relatively higher CIA values therefore, probably represented the reworked sediments derived from the adjacent older floodplain of modern Ghaggar river.

Based on ratios of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ in bulk silicates, it was recognized that HH and LH were the main contributors of the sediments to the core sites. However, their contributions varied over the time depending on variable sediment mixing from the two sources and glacial cover during different glacial–interglacial cycles. Climate controls on sediment erosion in the Himalaya were clearly reflected in the down-core variations of the Sr–Nd isotopes. During glacial periods, increased sediment contribution from LH was observed marked by distinctly higher $^{87}Sr/^{86}Sr$ and lower ε_{Nd} in the core sediments. This was because during glacial periods, there was an increase in glacial cover over HH whereas LH was relatively exposed for erosion. However, during interglacial periods the situation changed and relative erosion and sediment contribution was more from HH.

Cores from Indus Delta

Several sediment cores have been recovered and studied from the delta as well as offshore canyon of the River Indus in Pakistan, to study controls of climate over rates of continental erosion on millennial time scales (Figure 1). Clift *et al.*[25] studied these sediment cores from the Indus Delta (Keti Bundar, Thatta and Gularchy), the ages of deposition for which were calculated using AMS ^{14}C dating on mollusc shells, wood and plant remains. Out of three, the Keti Bundar core represents the deltaic sediments deposited during the Holocene and late Pleistocene, providing sediments with the maximum ages of 28.7 and 38.9 ka at the base (Figure 3). The late Pleistocene sediments, interpreted to have deposited after reworking and mixing of older sediments prior to transgression were assigned ages close to the LGM (>20 ka). Sediments provenance studies based on Nd isotopes, Ar–Ar dating of muscovites and U–Pb dating of zircons clearly established a major shift in the locus of sediment erosion in the Indus drainage basin since 20 ka from the Kohistan–Karakoram ranges in the north towards the LH ranges in the south. This provenance transition was best reflected in ε_{Nd} values that showed stepwise change during the late Pleistocene and early Holocene (at 14–20, 11–12 ka that is around the end of the YD and at 8–9 ka) (Figure 3). Relatively constant ε_{Nd} values after 8 ka suggested a more stable SW monsoon until a further decrease to around –14 is seen since last ~300 year ago. The shift in Nd isotope values suggested increased erosion and sediment fluxes from the LH and/or HH (or Greater Himalaya as given in original text) after 14 ka and during the early Holocene.

The study highlighted that the climate change had an immediate effect on the intensity and distribution of erosion over the orogen where the precipitation rather than temperature played the key control. Erosion of the LH and to some extent the HH, is closely associated with the strength of the SW monsoon. During strong SW monsoons, heavy rains penetrate deep north in the HH and rarely to the Karakoram where erosion is dominated by glaciation and precipitation by westerlies[52]. As the precipitation maxima appears to be largely focused over the LH as compared to the HH, strong early Holocene monsoon would have increased erosion and sediments fluxes from the LH ranges. Sediment buffering on the continental shelf avoided this variation to appear in the deeper regions of Arabian Sea but well-preserved in delta sediments with no apparent lag.

Marine palaeoclimate records

Andaman Sea

From the Andaman Sea, six sediment cores have been studied in detail that record changes in sediment provenance for the late Quaternary period. In the Andaman Sea, most of the sediments supplied are considered to be derived from the catchments in the Indo-Burman Ranges in western Myanmar, Central Myanmar Basin drained by the River Irrawaddy and its tributaries that bring sediments from further north. Additional minor contributions are from the small drainage systems on the Andaman Islands and rivers like Salween, Sittang and several others on the Southeast coast of the Malayan Peninsula[50].

Because the Andaman Sea is a semi-enclosed basin, it allows limited exchange of sediments with the adjoining Bay of Bengal and the South China Sea. The highly irregular bathymetries (with prominent seamounts and coral banks) of the basin, largely control the sediment depositions by turbidity currents whereas the deposition of pelagic sediments is governed by monsoonal surface ocean currents[53,54]. The entire basin has been divided into eastern and western sectors by a central deep valley[53]. Sampling details for the cores studied in the Andaman Sea are provided in Table 1 and discussed below whereas Sr and Nd isotope compositions of the potential sources contributing sediments to it are given in Table 2. $^{87}Sr/^{86}Sr$ and ε_{Nd} compositions of these cores with their sources are plotted in Figure 2 *b*.

Cores MD77-176 and MD77-169

Cores MD77-176 and MD77-169 studied by Colin *et al.*[33,55] were collected during cruise OSIRIS III of the R.V. Marion Dufresne in the year 1977. Core MD77-176 was collected off the mouth of River Irrawaddy from the South Preparis Channel connecting the Bay of Bengal and the Andaman Sea whereas core MD77-169 was raised from the Sewell seamount in the eastern Andaman Sea (Figure 1). Based on the Sr and Nd isotope compositions of the sediments from these and several other cores, Colin *et al.*[33] identified three sediment sources in the Andaman Sea. At both the core sites studied in these works, the River Irrawaddy dominated the sediment contributions followed by those originated from the Ganga–Brahmaputra (G–B) and small rivers on the western coast of the I–B Ranges. Because of its location, sediments of the core MD77-176 were characterized by slightly higher ε_{Nd} values similar to the composition of sediments in the eastern Bay of Bengal, suggesting higher sediment contributions from the I–B Ranges (Figure 4). As both the cores did not show any significant change in the ε_{Nd} values down core and over the time, a constant Irrawaddy source was suggested during the last two glacial–interglacial cycles. However, depending on supply of sediments controlled by erosion and weathering in the catchment, its proportion to the overall sediments was varied. The monsoonal variations in both these cores were best manifested in $^{87}Sr/^{86}Sr$ ratios that show change in values controlled by glacial–interglacial cycles. Glacial sediments were characterized by higher $^{87}Sr/^{86}Sr$ ratios than interglacial sediments due to enhanced physical erosions in the catchments during glacial times that resulted in production and efficient transport of high volumes of unaltered minerals rich in Rb.

Core SK-60-234

The core SK-60-234 studied by Awasthi *et al.*[54] shows a large variations in $^{87}Sr/^{86}Sr$ and ε_{Nd} values and in the relative contributions from different sources in last ~70 ka compared to other cores in the Andaman Sea (Figure 4). The core was taken ~32 km southeast of Barren Island Volcano in the western Andaman Sea (Figure 1). From the $^{87}Sr/^{86}Sr$ and ε_{Nd} compositions, a predominant I–B source was suggested for the clayey sediments at the core site. However, it was proposed that the sediments supplied to the core site were not directly sourced from the River Irrawaddy but rerouted from the north-eastern Bay of Bengal by currents driven by the monsoon. The Irrawaddy sediments dominate the shelves and deep-sea regions of eastern Andaman Sea. The supply of sediments with relatively positive ε_{Nd} values and low radiogenic $^{87}Sr/^{86}Sr$ at seven time periods (11–14, 20–23, 36, 45, 53, 57 and 62 ka) during the last glacial suggested enhanced contributions from the I–B sources during these times. Five out of these seven fluctuations were synchronous with the Heinrich cold events of the northern hemisphere. Therefore, a link between the changes in sediment provenances and changes in climate/monsoon was suggested. Glacial conditions observed strong NE monsoons and shifting of the locus of the SW monsoon, southward from the Himalayas, whereas interglacial conditions observed strong SW monsoons with its penetration to the interiors of the Himalaya. Within glacial and interglacial periods, there were several fluctuations in the SW and NE monsoonal intensities that also controlled the dispersion of sediments in the Andaman Sea by controlling the direction and strength of surface currents.

Core SK-168-GC01

Core SK-168-GC01 was collected 60 km south-east of SK-60-234 on Alcock seamount (Figure 1)[56]. The core provides a high-resolution record of terrigenous sediment input of about 54 ka tracking temporal variations in the monsoon, weathering patterns and provenance changes. Based on the unradiogenic ε_{Nd} values, the Salween and Sittang river basins ($\varepsilon_{Nd} = -14.7$ to -15.4) along with Irrawaddy ($\varepsilon_{Nd} = -8.3$ to -10.7) were recognized as main contributors of detrital sediments to the core site throughout the studied interval. The minor variations in the $^{87}Sr/^{86}Sr$ and ε_{Nd} values with time were suggested to be due to changes in chemical weathering and erosion in the river catchments of Myanmar that were controlled by the climate (Figure 4). The glacial sediments showed higher $^{87}Sr/^{86}Sr$ ratios and unradiogenic Nd values, whereas interglacial sediments reflected values with low $^{87}Sr/^{86}Sr$ ratios and high radiogenic Nd values. It is said that higher $^{87}Sr/^{86}Sr$ ratios during glacial times were result of the predominant physical weathering as observed in the core MD77-169 studied by Colin *et al.*[33]. The low sea levels with the exposed shelves and weakened eastward flowing currents during the glacial times would have

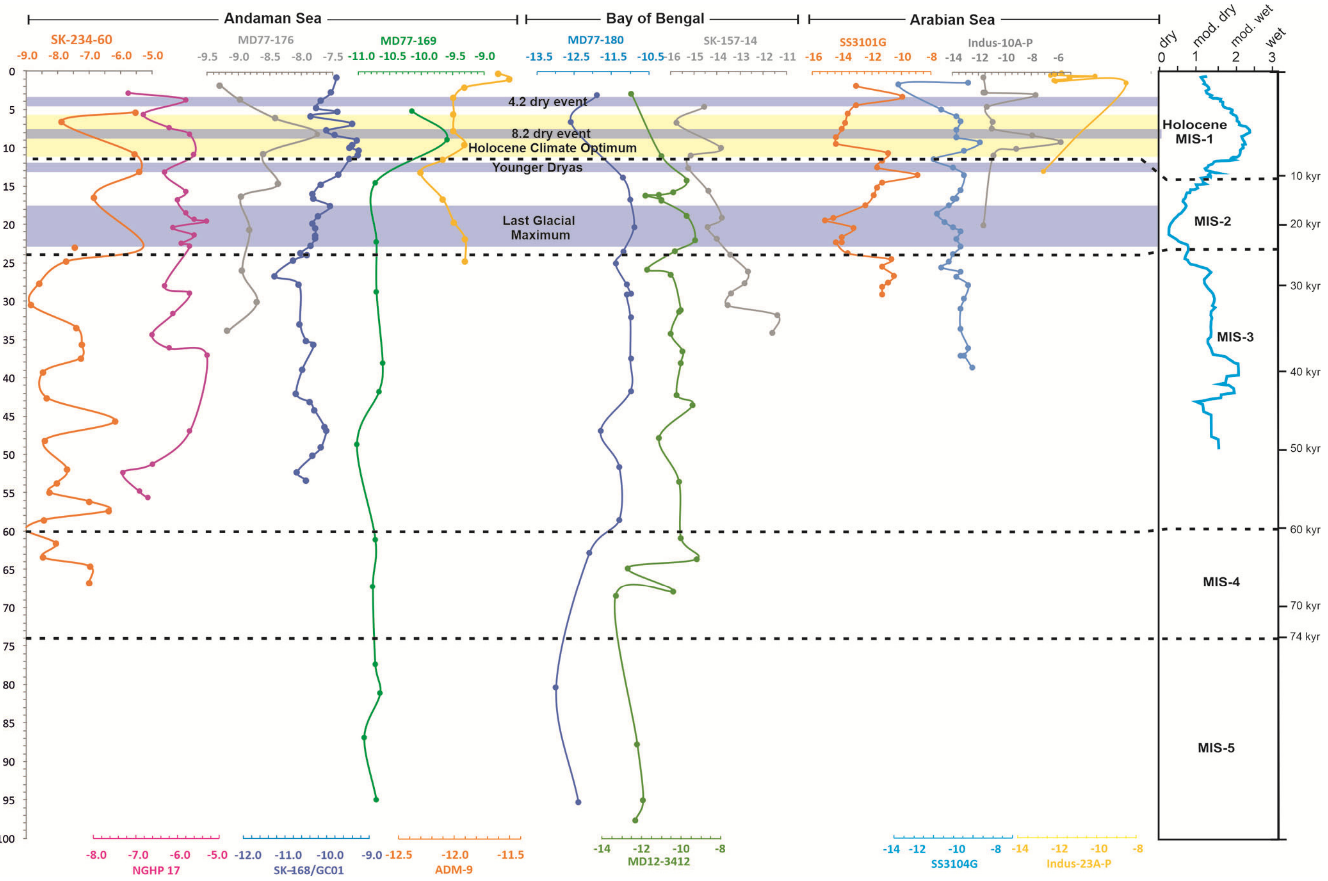

Figure 4. Plot of ε_{Nd} variations in marine sediment cores from the Andaman Sea, the Bay of Bengal and the Arabian Sea compared with records of mean effective moisture of the Asian Monsoon during the last 50 ka (ref. 9). MIS, Marine isotopic stage.

isolated Irrawaddy from Salween and Sittang sources due to which there was more supply of sediments with the unradiogenic Nd values derived from the Salween and Sittang rivers to the central-eastern Andaman Sea during these times. This was supported by the strong NE monsoons during the glacial times. With the transition to warmer climates after arid climatic phase of LGM and during the interglacial times, particularly during the 9–7 ka the chemical weathering increased producing lower radiogenic $^{87}Sr/^{86}Sr$ values. The high radiogenic ε_{Nd} values were observed during 53 to 42 ka and 15.5 to 5.5 ka. The 53–42 ka event occurred during low summer insolation and coincided with Heinrich event-5 known from the North Atlantic Ocean. The high radiogenic ε_{Nd} values during 15.5 to 5.5 ka mark the beginning of warmer climate, deglaciation and increased monsoon after LGM. There was no major change in ε_{Nd} during the LGM.

Core NGHP-17

The core NGHP-17 in the western Andaman Sea studied by Ali *et al.*[57], reported no major change in ε_{Nd} values over the studied time interval of the past 60 ka (Figures 1 and 4). Based on the Nd isotope compositions, clays at the core site were interpreted to be mainly sourced from the catchment in the Irrawaddy basin, predominantly from the I–B Ranges with a minor contribution from nearby local sources like the Andaman Islands and Barren Island Volcano. As source of the detrital clays did not change significantly during the last glacial and deglaciation, it was suggested that the monsoon over the Irrawaddy catchment was spatially stable during this time, an interpretation in contrast with the study of the core SK-234-60 and other cores in the Andaman Sea that show noteworthy variations for the same time. However, other proxies like ratios of clay minerals and $^{87}Sr/^{86}Sr$ from the same core suggested that monsoon was weaker during the glacial period and stronger during the Holocene deglaciation. The weaker monsoon intervals were marked by drier conditions with sediments poor in smectite and highly radiogenic $^{87}Sr/^{86}Sr$ compositions. These weaker phases of monsoon intensity were well-correlated to the short-term Heinrich cold events of north Atlantic.

Core ADM-9

A sediment core ADM-9 studied by Cao *et al.*[58] was taken ~350 km southeast of previous core (NGHP-17)

(Figure 1). The dating of the core revealed that it covered the time interval of 26 ka (Figure 4). The Nd isotope values of the terrigenous sediment recognized the Irrawaddy river as a dominant source to the south-eastern continental slope of the Andaman Sea. The ε_{Nd} values do not show much variation except a highly unradiogenic value at ~13 ka and a shift to radiogenic ε_{Nd} values in last ~2 ka (Figure 4). The unradiogenic ε_{Nd} value at ~13 ka in the core ADM-9 might be due to increased contributions from the Salween and Sittang rivers during the strong NE monsoons of YD. The change to highly radiogenic ε_{Nd} values in last ~2 ka was probably due to strengthening of the SW monsoon and increased proportion of sediment supply from the River Irrawaddy. However, other proxies like grain-size, major elements and $^{87}Sr/^{86}Sr$ ratios the reconstructed high-resolution record suggest a weaker SW monsoon during ~26–15 ka that strengthened gradually to its peak during ~9–7 ka during the early Holocene. Since then, a declining trend is observed in the SW monsoon, particularly from ~2 ka BP during the late Holocene. Beside these, the SW monsoon was also strong during the B–A period and weak during the YD and at 8.2 ka within the strong monsoon period of ~9–7 ka, indicating the atmospheric teleconnection of Asian climate with the climate in the North Atlantic.

Bay of Bengal

A total of four sediment cores have been studied from the Bay of Bengal that provide long-term record of change in sediment provenance and interpreted climate based on that. In the Bay of Bengal, sediment flux of almost 1×10^9 tonnes is supplied annually only through the combined delta of G–B Rivers[59]. Out of the total sediment discharge, about 90–95% is transported only during the SW monsoonal months of June to September[27,60]. These sediments are mainly derived from the catchments in the Himalayas with relatively minor contributions from the peninsular region of India and the I–B Ranges. The sediments derived from the peninsular rivers have restricted spatial extent. The floor of the Bay of Bengal is completely covered by the Bengal Fan, which is the largest submarine fan in the world largely made up of sediments derived from the uplift and erosion of the Himalayas and Tibetan Plateau and turbiditic sedimentation since the Oligocene/Early Miocene[61–63]. Although a huge amount of the sediment is sourced from the Himalayan and peninsular rivers, there is open possibility of exchange of sediments with adjoining seas. Sampling details for the cores studied in the Bay of Bengal are provided in Table 1 and discussed below. Table 2 gives Sr and Nd isotope compositions of the potential source regions and rivers. $^{87}Sr/^{86}Sr$ and ε_{Nd} compositions of these cores with their sources are plotted in Figure 2 *c*.

Cores MD-77-180 and MD12-3412

Cores MD77-180 and MD12-3412 were collected near the continental slope, in the upper part of the Bengal deep-sea fan during the French expedition of R/V Marion Dufresne in the years 1977 and 2012 respectively[64] (Figure 1). The cores were primarily made up of clay and silt size sediments accumulated both by relatively continuous hemipelagic deposition and episodic sediment gravity-flow deposition. Based on the age models established by using high-resolution oxygen isotope stratigraphy and AMS ^{14}C dates on planktonic foraminifers, the core MD77-180 was dated to ~160 ka and core MD12-3412 to ~182 ka (Figure 4). The Sr and Nd isotope data of detrital fraction of sediments suggested multiple sources contributed to the studied core sites in the eastern part of the Bay of Bengal that mainly include sediments from the G–B rivers mixed with the sediments from the Irrawaddy river and rivers from the Arakan coast[33]. G–B rivers transfer sediments derived from the Himalayas whereas the rivers like Irrawaddy and those from the Arakan coast supply sediments derived from the I–B Ranges. A higher proportion of these materials was transported by oceanic currents. Based on variations in multiple proxies like clay minerals, siliciclastic grain-size, major elements, Sr and Nd isotope compositions of sediments through time, it was inferred that during the glacial times there was an increase in sediment contribution from the I–B Ranges to the eastern part of the Bay of Bengal. A dominant NE monsoon during the glacial periods (MIS2, 3, 4, and 6) brought changes in the sea circulation pattern and/or sea-level lowering that resulted in enhanced contribution of sediments from the I–B Ranges. On the contrary, during interglacial periods (MIS 1 and 5) there was a higher contribution of G–B river sediments resulted from the strengthening of the SW monsoon.

Interglacial periods observed relatively low sedimentation rates at the core sites and sediments deposited were mainly transported by surface or subsurface currents. In contrast, glacial periods had higher sedimentation rates and sediments deposited dominantly by strong turbidity currents induced by a sea level low-stand and were coarser in size. In clay mineral ratios, the glacial periods showed an increased input of detrital material derived from intensive physical erosion and moderate chemical weathering of metamorphic (i.e. muscovite or biotite) and granitic parent rocks, or reworking of sedimentary rocks from the highlands of the river basins. Interglacial periods are characterized by a relative increase of smectite content most likely derived from higher physical erosion and/or chemical weathering in the G–B flood-plains. The intensification of the SW monsoon rainfalls during the warm inter-glacial periods would have generated sediments rich in smectite by the chemical weathering of parent alumino silicates and ferromagnesian silicates. The increased water flux and enhanced summer surface currents pattern in the north-eastern Bay of Bengal could have efficiently transported these sediments.

Core SK-157-14

The core SK-157-14 was retrieved from the 90° East Ridge in the south-eastern Bay of Bengal (Figure 1). Age model for the core suggested a continuous sedimentary record from about 2.6 to 43 ka BP (Figure 4). Sr and Nd isotope compositions of the terrigenous material in the core clearly demonstrated a dominant contribution from the Irrawaddy-derived fluxes with minimum contributions from the G–B and/or peninsular Indian river sources. It was suggested that the core site remained devoid of sediments derived from the G–B sources because of the strong westward currents that diverted most of the sediments towards the abyssal plains. $^{87}Sr/^{86}Sr$ and ε_{Nd} values at the core site show a systematic variability that can be related to oscillations in climate with change in the relative strengths of Indian SW and NE monsoons on shorter time scales. It was suggested that during the phases of strong NE monsoon (e.g. at 5–7, 14, 19, 25 and 31–33 ka BP), there were increased supply of Irrawaddy-derived sediments with low $^{87}Sr/^{86}Sr$, higher radiogenic Nd and high silt content. Strong currents of NE monsoon brought more silt-sized fraction from the Irrawaddy source. The phases of intensified NE monsoon were linked to the rapid cold events of North Atlantic (Heinrich events).

Core SK187/PC33

The 12.8 m long core SK187/PC33 was collected from the abyssal plain in western Bay of Bengal off the delta of River Mahanadi and studied by Tripathy *et al.*[34] (Figure 1). The core was made up of silty-clayey sediments sourced mainly from the Himalaya (~60%) with minor (~40%) contributions from the peninsular Indian region. A high-resolution analysis of Sr and Nd isotope compositions along with magnetic susceptibility and elemental ratios (Fe/Al, V/Al) of the sediments show variable contributions from different sources with time (Figure 4). These temporal changes in the sediment provenance were well-correlated with the variability in the strength of the Asian monsoon. The monsoon has major influence over erosion and thus on supply of sediments to the rivers and seas. Like many other cores in Bay of Bengal and Andaman Sea, this core too observed relatively lower $^{87}Sr/^{86}Sr$ and higher ε_{Nd} during the LGM compared to the compositions before and after the LGM. This was due to reduced share of sediments sourced from the Himalaya relative to the peninsular Indian rivers, particularly the sediments with highly radiogenic Sr carried by the River Ganga. The LGM period observed reduction in supply of sediments due to weak intensity of SW monsoon and decreased erosion over the HH that was covered by glaciers to a larger extent. However, NE monsoon was strong that resulted in substantial supply of sediments from the peninsular river basins. The inferences from the Sr, Nd isotopes were confirmed by the higher V/Al and Fe/Al ratios and the magnetic susceptibility values also suggested relatively enhanced sediment supply from the peninsular Indian rivers during the LGM.

Arabian Sea

From the Arabian Sea, four sediment cores have been studied for provenance interpretations and their implications to climate, sea-level changes and ocean current circulation patterns. The Arabian Sea covers a total area of about 3,862,000 sq. km in the northern Indian Ocean. The sea gets its major supply of sediments through the Indus river system that annually supplies ~400 million tonnes of sediment sourced from the Himalaya and Trans-Himalaya[65] whereas the rest (~100 million tonnes) is contributed by the Narmada, Tapi and other rivers originating in the Western Ghats[66]. The Himalayan and Trans-Himalayan sediments predominate in the northern and central regions of the Arabian Sea[67], whereas off the broad continental shelf surrounding the eastern Arabian Sea and in the slope regions mainly peninsular Indian sources control the sedimentation[67,68]. The shallow shelf regions act as a sink for sediments transported by the Western Himalayan and Indian peninsular rivers[68–70]. Goswami *et al.*[71] suggested a long-range transport of G–B sediments from the Bay of Bengal to the tip of Indian peninsula by surface currents. Moreover, because of its location adjacent to the great Saharan desert in Africa and small deserts in Arabia, Oman and western India, the Arabian Sea receives additional annual inputs of aeolian dust (~100 million tonnes) that blows from these deserts[72]. The water and sediment discharge in the Arabian Sea is strongly seasonal, with the majority occurring during the summers when glacial melting and monsoon precipitation is maximum[48]. Therefore, the sediments deposited preserve the records of erosion in their drainage basins that is mainly controlled by the monsoon[25,26]. Sampling details and Sr and Nd isotope compositions of the potential sources regions and rivers for the cores studied in the Arabian Sea are given in Tables 1 and 2 respectively. $^{87}Sr/^{86}Sr$ and ε_{Nd} compositions of these cores with their sources are plotted in Figure 2 *d*.

Cores Indus-10A-P and Indus-23A-P

The cores Indus-10A-P and Indus-23A-P were raised from the shallow waters of ~120 km broad Indus Shelf that acts as a sink for the sediments mainly eroded from the Karakoram and Western Himalayan regions and brought by the river Indus and its tributaries[70,68] (Figure 1). Both the cores are principally composed of clay-rich, muddy material that contains sporadic layers of silt. The

^{14}C dating on the mollusc shells within the cores reveal that these cores represent sedimentation spanning the Early Holocene to present (<14 ka; Figure 4). The core Indus-23A-P collected close to the modern Indus River mouth and canyon show a maximum age of 13.7 ka at the bottom of the core (Figure 4). However, a major break in accumulation between 7.8 ka and 1.5 ka was also observed at the core site. The core Indus-10A-P sampled ~130 km northwest of the canyon provides a continuous sedimentation record of ~11 ka.

Provenance analyses based on geochemical and isotope data suggest that the core Indus-23A-P directly received sediments from the Indus River mouth mixed with some older Indus sediments whereas in the Indus-10A-P core a significant proportion of the sediment was originated from the Bela Ophiolite through the Hab River in the southwest Pakistan, rest of the material was sourced either directly from the Indus river or from reworking of its shelf deposits. It was observed that the sedimentation at both the sites was highly influenced by the climate variations and resultant erosion in the source regions of sediments, change in sea-levels and long shore surface currents. The source regions for the rivers in Pakistan are affected both by the southwest monsoon and the westerlies that are known to have varied with time. The long shore surface currents observed today were developed only after the rise in sea-level following the LGM[73].

The basal sediments of the core Indus-10A-P were strongly weathered, probably representing the deposition on the exposed shelf when the sea level was low during the last glacial. The sediments deposited during the early Holocene (11 ka to 8 ka) were chemically less weathered and had higher ε_{Nd} values compared to the Indus sediments, suggesting sediment supply from the Bela Ophiolite sources was at its peak during that time. This was made possible by drift in the position of long shore currents close to the coast after the Early Holocene transgression that resulted in supply of sediments to the core site. The hiatus in core Indus-23A-P from 8 ka until 1.3 ka indicates either no sediment deposition during that time or erosion of deposited material. The core provides the record of the last 1600 years showing dominant contribution from the Bela Ophiolite like sources at 1.3 ka. The exact source could not be identified but appears to be deposited by reworking of older delta sediments.

For the core Indus-10A-P, ε_{Nd} values did not show any correlation with the monsoon history suggesting the provenance of the sediments was consistent throughout and not influenced by monsoonal changes. Several studies based on various climate proxies indicate a strengthening of the SW monsoon between 11 ka and 8 ka. Comparison of monsoonal records with chemical weathering proxies (CIA, K/Al, Mg/Al and $^{87}Sr/^{86}Sr$) indicates reduction in the flux of eroded carbonate after 11 ka until 8 ka. The record also indicated, there was a gradual increase in silicate weathering between 11 ka and 4.5 ka. However, inconsistencies in trends of carbonate and silicate chemical weathering proxies were reported when compared with the known variability of the SW monsoon[74,75] and a lag of 4–5 ka was observed between the peaks in the intensities of monsoon strength and weathering.

Cores SS-3104G and SS-3101G

The core SS-3104G was raised from the deep-sea north of Chagos Laccadive Ridge off the coast of Mangalore whereas the core SS-3101G was taken ~800 km south of the previous site in the south-eastern Arabian Sea (Figure 1). The two cores were dated using AMS ^{14}C dating technique on planktonic foraminifers[76,77]. The core SS-3104G represents a depositional history of ~40 ka, while the core SS-3101G covered a time period of ~29 ka (Figure 4). The $^{87}Sr/^{86}Sr$ and ε_{Nd} values of the silicate sediments in core SS-3104G did not show much variation throughout its length, suggesting no major change in the provenance of sediments and their mixing proportion during the studied interval (Figure 4). The sources that contributed sediments to the core site (SS-3104G) were mostly the rivers like Indus, Narmada, Tapi and other Western Ghats streams. In contrast, the core SS-3101G showed wider range in Sr and Nd isotope compositions although their maximum and minimum values were similar to that observed for the core SS-3104G. Deccan basalts and the Vindhyan Supergroup sediments carried by the Narmada and the Tapi rivers were considered as the dominant sources to this core (Figure 4).

The core SS-3101G showed two major excursions in $^{87}Sr/^{86}Sr$ and ε_{Nd} compositions at ~9 ka and at ~20 ka (Figure 4). These two excursions were also seen in the climatic (monsoon) variation record known from the Asian region as provided in Herzschuh[9]. The ~20 ka variation corresponded to the changes in erosion patterns and ocean circulation during the LGM. The Sr and Nd isotope composition in the core showed a peak in $^{87}Sr/^{86}Sr$ and a dip in ε_{Nd} values during the LGM. This was either due to relative increase in sediments from the Himalaya contributed through the Indus and/or due to higher sediment flux derived from granites/gneisses in peninsular India. Both the regions were either affected by westerlies or NE monsoon precipitation that is known to have intensified during the LGM[9]. Moreover, the intensification of NE monsoon during LGM resulted in strengthening of the south-westward East Indian Coastal Current (EICC) in the Bay of Bengal that enhanced the flow of waters and sediments from the Bay of Bengal to the core site in the Arabian Sea[78,71]. However, provenance interpretations based on sediment clay mineral studies from south-eastern Arabian Sea suggested a different scenario. It did not consider any sediment input from the Bay of Bengal instead an enhanced contribution from peninsular granites/gneisses during this time through the Nethravathi and Periyar rivers[69].

The excursion in isotope compositions at ~9 ka overlapped with the known event of SW monsoon intensification during the early Holocene, also known as 'Holocene Intensified Monsoon Phase' (IMP)[9,74]. In contrast to situation encountered during the LGM with weak SW monsoon, this period observed many folds increase in precipitation throughout the continent. However, as the sea level was highly similar to that at present, sediments generated from the small west-flowing peninsular streams were retained to the shelf region of the Arabian Sea[79]. The observed variations in the isotope compositions were explained by considering either the enhanced supply of sediments by the Narmada and Tapi rivers or due to increased contributions from the Indus delta. Narmada and Tapi rivers were considered as the major suppliers of sediments to the Arabian Sea after Indus and would have supplied more sediment during the early Holocene as their drainage basins are dictated by SW monsoon. Studies from the Indus delta also displayed similar variations in isotope compositions during ~9 ka that hinted towards the possibility of supply of Indus delta sediments to the SS-3101G core site[25,80]. If that was the scenario, the isotope compositions could be explained by enhanced sediment supply through the Indus tributaries resulted from the increased SW monsoon precipitation over the Himalaya during this period. Also, IMP resulted in stronger surface currents that transported water and sediments in the southeast direction from the Arabian Sea towards Bay of Bengal. The location of the core SS-3101G was ideal to receive that sediment contribution by surface currents.

Summary

The multi-proxy data on provenance from both terrestrial and marine sedimentary records suggest that within chronological constraints the sediment provenances have been highly sensitive to well-defined major climatic events occurred during the late Quaternary. The following points emerge from this review based on provenance studies:

- The IITK core showed two major and two minor phases of weak SW monsoon intensity with reduced precipitation and extended glaciers in HH source regions at ~20, ~70 ka and ~40, ~90 ka respectively. These periods saw decrease in the proportion of sediments supplied from the HH sources.
- The Firozpur core showed that the Ganga valley aggradation started before ~31 ka under humid climatic conditions. During the pre-LGM times, the HH sources dominated the sediment contribution (~100%) which ceased during the LGM due to low rainfall during weak monsoon conditions. After LGM, there was a relatively higher (~30%) contribution from the LH sources.
- Trends from the Cores GS-10 and GS-11 (Ghaggar river plains), suggested a relatively higher sediment contributions from the LH sources during glacial periods and HH sources during interglacial periods.
- The Indus delta cores showed a transition from the Trans-Himalayan sources towards the LH and/or HH sources since 20 ka, prominently observed after stronger SW monsoon phases associated with B–A and early Holocene events. The SW monsoon achieved stability after 8 ka.
- Cores MD77-176, MD77-169 and SK-168-GC01 from the Andaman Sea suggested that the physical weathering in the catchments enhanced during the arid and cold climate of glacial times. Low sea levels and weakened eastward flowing currents during these times resulted in a relatively higher contribution of sediments from Salween and Sittang sources to the central-eastern Andaman Sea.
- Core SK-168-GC01 also suggested that during the 9–7 ka (early Holocene), the chemical weathering and supply of sediments sourced from I–B Ranges increased under stronger SW monsoon conditions.
- The cores NGHP-17 and ADM-9 do not show much variation in provenance but supported interpretations from the other studies of weaker monsoon during the glacial periods and stronger monsoon during the Holocene deglaciation. The core ADM-9 also suggested that during ~26–15 ka, YD and at 8.2 ka, the SW monsoon was weaker and NE monsoon was stronger similar to climate records from other studies. There was strengthening of the monsoon during the early Holocene (~9–7 ka) followed by a declining trend during the late Holocene particularly, from ~2 ka BP.
- The core SK-60-234 suggested sediments to the western Andaman Sea were derived from the I–B Ranges that were rerouted from the north-eastern Bay of Bengal by the monsoon-driven currents. Relative sediment contributions from the I–B sources enhanced during the strong NE monsoons conditions of last glacial, particularly at seven time periods (11–14, 20–23, 36, 45, 53, 57 and 62 ka). These climatic conditions also controlled the dispersion of sediments in the Andaman Sea by changing the direction and strength of surface currents.
- In similar manner to the cores in the Andaman Sea, sediment cores (MD77-180 and MD12-3412) from the central and NE Bay of Bengal also suggested increase in physical erosion and contribution from the I–B Ranges during the glacial periods (MIS 2, 3, 4 and 6) along with considerable changes in the sea circulation pattern and rise in sedimentation rates. During the interglacial periods (MIS 1 and 5) when the sea levels were relatively higher, sediment depositions were mainly by surface or subsurface currents and the G–B river sediments dominated the contribution.
- The core SK-157-14 recognized increased supply of Irrawaddy-derived sediments during the phases of strong NE monsoon (e.g. 5–7, 14, 19, 25 and

31–33 ka BP) that were well-correlated to the rapid cold events of North Atlantic (Heinrich events).
- The core SK187/PC33 site observed reduction in supply of sediments from the Himalaya relative to the peninsular Indian sources during the LGM under weak SW monsoon conditions.
- The basal sediments in the core Indus-10A-P were deposited on the exposed shelf during the last glacial. The core site started receiving sediments from the Bela Ophiolite sources during the early Holocene (11 ka to 8 ka), due to drift in the position of long shore currents close to the coast. Similar contribution from the ophiolite sources was observed in the core Indus-23A-P at 1.3 ka. Chemical weathering records suggested a gradual increase in silicate weathering between 11 and 4.5 ka.
- The excursion at ~20 ka in the Arabian Sea core SS-3101G suggested change in erosion pattern and relative increase in contribution of sediments from the Himalaya and/or peninsular Indian sources during the LGM as both westerlies and NE monsoon intensified. The variation at ~9 ka corresponded to event of SW monsoon intensification during the early Holocene that resulted in enhanced supply of sediments by the Narmada and Tapi rivers as their drainage basins are dictated by SW monsoon.

Conclusion

Interpretations based on changes in sources and various other proxies during the last glacial–interglacial cycles suggested a strong atmospheric teleconnection of Asian climate with the climate in the North Atlantic. However, depending on its location and local geography, the duration and intensities of the climatic events have varied on regional scale. Sediment cores from the Ganga and Indus plains mainly deriving sediments from the HH, LH and Trans-Himalayan sources clearly reflected that the variations in the climate/monsoon precipitation and/or change in glacial extant played key control in varying weathering/erosion patterns in source regions and proportional mixing of sediments carried by the rivers. Marine sediment cores taken from the Andaman Sea, Bay of Bengal and Arabian Sea showed more continuous and long-term record as compared to terrestrial sources. However, these records have been found to be influenced by additional factors of changes in land–sea configuration such as low stand of sea-levels, migration of shorelines, river mouths, and deltas compared to changes in sediment sources and erosion observed on land. Changes in sea surface-circulation also largely influence the efficiency of transport of sediments. Therefore, making interpretations based on marine sediment data are complicated. Overall, from these studies a declining trend of the Indian SW monsoon intensity was observed during the last ~100 ka interspersed with periods of relatively strong SW monsoon/higher precipitation (~60 to 30 ka). The arid phase of climate peaked during the LGM around 20 ka marked by weak SW monsoon, increased physical weathering in the sources and decreased HH contribution. The SW monsoon started strengthening after LGM with rise in sea-level and by the early–mid Holocene (11.5–5.5 ka), wetter and cooler climate with stronger monsoon conditions re-established. At most of the sites, this phase also known as 'Holocene Climate Optimum', was interrupted by an abrupt cooling event at ~8.2 ka. The favourable monsoon conditions increased the sediment carrying capacity of rivers resulting in supply of higher sediment fluxes mainly derived from LH sources to the seas. The late Holocene period after ~5.5 ka again observed a declining trend of SW monsoon. The weakest phase of SW monsoon was observed around 4.2 ka with relatively colder and drier conditions and a persistent record of aridification.

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