

A glimpse of the Quaternary monsoon history from India and adjoining seas

Rajeev Saraswat¹, Rajiv Nigam¹, Thierry Correge²

1 National Institute of Oceanography, Goa, India

2 Univ. Bordeaux, EPOC, UMR 5805, F-33400 Talence, France

Abstract

The evolution of the monsoon is briefly summarized taking into account previous studies conducted on both terrestrial and marine records recovered from the Indian subcontinent and the adjoining seas. While the initiation of the monsoon is debated, it seems clear that a major intensification of the summer monsoon occurred at ~8.2 Ma. A seasonal monsoon circulation with distinct summer and winter monsoon phases was established at ~2.8 Ma. In the Late Quaternary, the summer monsoon weakens during glacial periods as compared to interglacial periods. The centennial to sub-centennial scale changes in the monsoon during both glacial and interglacial periods suggest strong links between high latitude processes and the tropical monsoon and its role in modulating northern hemispheric climate. The glacial terminations are marked by weak monsoon activity. The summer monsoon weakened during the Middle Holocene after the Early Holocene optimum. A change in the monsoon intensity though alters the salinity of the seas surrounding India, the quantitative paleosalinity reconstructions still have large associated uncertainties and an effort should be made to lower them.

Introduction

The Indian subcontinent is amongst one of the most densely populated regions of the world. Agriculture is the main source of income and livelihood for the majority of people residing in this region. Agriculture in the Indian subcontinent largely depends on monsoon precipitation with about 65% of the total cultivated area, accounting for almost half of the total food grain production, being solely dependent on rains for irrigation (Gadgil et al., 1999). The monsoon in this region has two distinct phases, viz. the southwest monsoon (from June to September, also termed as the Summer Monsoon) which brings most of the precipitation over India, and the northeast monsoon (November to February, also termed as the Winter Monsoon), that causes heavy rains over the equatorial Indian Ocean and the region further south of the equator (Figure 1). Any change in monsoon precipitation affects the food grain production (Gadgil et al., 1999) and the regional hydrological balance. The tropical monsoon has been suggested as a key modulator of the climate of the northern hemisphere (Kudrass et al., 2001; Ivanochko et al., 2005). Besides, the tropical monsoon is also a key factor during global ice-age terminations. It has recently been proposed that ice-age terminations are marked by prominent weak monsoon interval (Cheng et al., 2009; Saraswat et al., 2013). Therefore, it is important to understand the factors governing the monsoon as it will help in refining the global circulation models used for predicting the future monsoon changes.

Initially, the Asian monsoon was described as a giant sea breeze resulting from land-ocean temperature contrast (Halley, 1686). The cooling of the Asian landmass following the initial precipitation suggested, however that the land-ocean thermal contrast, though, may be responsible for monsoon onset, cannot sustain the persistent 'sea breeze' which brings precipitation over several months (Simpson, 1921). An inverse relationship between snow cover over the Himalaya during the preceding winter and spring season and summer monsoon precipitation was initially suggested by Blanford (1884) and later confirmed by Walker (1910) as well as Vernekar et al (1995). Flohn (1968) suggested that the western Tibetan Plateau which acts as a source of sensible heat, as well as the orographically released latent heat over the southeastern Tibet, sustains the atmospheric circulation responsible for the monsoon. Modeling studies confirmed the importance of the presence of high mountains in the north in both initiation and sustenance of the monsoon (Hahn & Manabe, 1975). Modeling studies further confirmed the effect of global as well as regional orography of the Asian region on Indian summer monsoon

rainfall. The summer precipitation is influenced relatively more by the orography west of 80°E than that to the east of 80°E. The precipitation during summer monsoon season increases by 28%, without the African orography, while the absence of global orography reduces the precipitation by 25% (Chakraborty et al., 2002). Monsoon as a manifestation of north-south movement of inter-tropical convergence zone was proposed by Charney (1969) and later confirmed by Gadgil (2003). The sea surface temperature of the adjacent ocean (Shukla, 1975; Rasmusson and Carpenter, 1983; Li et al., 2001; Yang et al., 2007), regionally coupled phenomena including El-Nino Southern Oscillation (Krishna Kumar et al., 1999; Lau and Nath, 2000; Krishnamurthy and Kirtman, 2003; Gadgil et al., 2004; Ilhara et al., 2007), Indian Ocean Dipole (Ashok et al., 2004; Kripalani and Kumar, 2004; Ilhara et al., 2007), ice-sheet extent in both the northern and southern high latitudes (Schulz et al., 1998; Kudrass et al., 2001; Gupta et al., 2003; An et al., 2011; Saraswat et al., 2013), insolation (Agnihotri et al., 2002; Tiwari et al., 2005; Gupta et al., 2005; Clemens et al., 2010; Caley et al., 2011) have also been suggested as the key factors that control geographic extent and intensity of the monsoon in the Indian subcontinent on both short and long time scales.

Long-term past monsoon records can help understand monsoon dynamics, especially the ocean-atmosphere coupling. Such past monsoon records have previously been reconstructed from both terrestrial as well as oceanic archives using different proxies. The terrestrial and marine archives and the proxy carriers therein, are controlled by different sets of physico-chemical and biological factors, which may lead to biases in the monsoon records from these archives. Inter-comparison of the past monsoon records from both the terrestrial and marine realms help give a synoptic view of monsoon changes in the Indian subcontinent and nearby oceanic regions. In view of this, in this special issue we bring together articles based on past monsoon records generated from both terrestrial (India) and marine (mostly the Indian Ocean) archives. The idea for this special issue materialized during the 7th International Conference on Asian Marine Geology (ICAMG) held in Goa from 11 to 14 October 2011. Out of the total six articles, a few papers were presented in the ICAMG.

A Glimpse of Previous Paleomonsoon Studies

A. Paleomonsoon Proxies

Past monsoon changes have been reconstructed from both terrestrial as well as marine archives recovered from both the Indian subcontinent as well as the adjacent seas. The initial past summer monsoon intensity records reconstructed from the western Arabian Sea relied on the increased abundance of planktic foraminifera *Globigerina bulloides* in nutrient-rich cold water that upwells to the surface in response to the winds blowing from the southwest. These winds bring moisture to the Indian subcontinent and are responsible for precipitation in this region during the summer season (Kroon et al., 1991; Prell et al., 1992). Subsequently, a wide variety of organo-bio-geochemical proxies, including characteristics of marine microfossils, grain-size, magnetic susceptibility, clay mineralogy (Sirocko et al., 1993; Chauhan et al., 2000; Thamban et al., 2002; Kessarkar et al., 2005; Rao et al., 2010), total organic carbon content (Schulz et al., 1998; Kudrass et al., 2001), major, minor and trace element composition of the sediments (Sirocko et al., 2000), and stable isotopic ratio of selected elements (Tripathy et al., 2011) have often been used to infer past monsoon changes from cores collected in the Indian Ocean.

A large number of paleomonsoon records reconstructed so far from the Indian Ocean are based on microfossils, including foraminifera, radiolarians (Gupta, 2003), diatoms, ostracodes (Jin et al., 2009), coccolithophores, pollens, spores (Prell and Campo, 1986; Prabhu et al., 2004), alkenone (Rostek et al., 1993), corals (Ahmad et al., 2011), and other microfossils. Temporal changes in pteropod abundance and diversity have also been interpreted in terms of monsoon induced changes in physico-chemical conditions along with sea-level changes (Almogi-Labin et al., 1991; Böning and Bard, 2009; Sijinkumar et al., 2010). Changes in relative abundance, morphology (Nigam et al., 1995), species assemblage and diversity (Heinz and Hemleben, 2006), shell weight (Naik et al., 2010), stable isotopic and trace metal ratio of the fossil calcareous shells (Dahl and Oppo, 2006; Anand et al., 2008; Banakar et al., 2010; Govil and Naidu, 2011; Saraswat et al., 2012; 2013), are frequently used to infer past monsoon changes from the Indian Ocean. Lake sediments (Prasad et al., 1997; Sharma et al., 2004; Wünnemann et al., 2010), peat deposits (Sukumar et al., 1993; Hong et al., 2005), ice-cores (Thompson et al., 1997; 2006), loess-paleosol sequences (Singhvi et al., 2001), trees (ring width and stable isotopic composition) (Ramesh et al., 1985; Yadav, 2013) and speleothems (Burns et al., 2002; Sinha et al.,

2005; Fleitmann et al., 2007; Kotlia et al., 2012), are some of the major archives that have been used to infer past monsoon changes from the Indian subcontinent. Paired measurement of stable oxygen isotopic ratio and trace metal composition (Mg/Ca, a proxy for seawater temperature) of surface dwelling planktic foraminifera in cores collected from the continental shelf region helps in estimating past salinity which is mainly controlled by local evaporation-precipitation, thus providing a good idea about monsoon intensity (Dahl and Oppo, 2006; Anand et al., 2008; Banakar et al., 2010; Govil and Naidu, 2011; Saraswat et al., 2012; 2013).

B. Initiation of Monsoon

The long-term past monsoon records reconstructed from the sites drilled as a part of the Ocean Drilling Program and Deep Sea Drilling Project, have helped to infer initiation, major phase shifts as well as changes in seasonality of the Indian monsoon. The timing of initiation of the Indian monsoon system is debated (Clift et al., 2008). The presence of typical upwelling indicator fauna in the western Arabian Sea sediments, however suggests a possible initiation and a definite major intensification of summer monsoon at ~8.2 Ma (Kroon et al., 1991; Prell et al., 1992). A close link between onset (9-8 Myr ago) and further evolution of the monsoon and phased uplift of Himalaya-Tibetan plateau was suggested based on the past monsoon records from China and the Indian and North Pacific oceans (An et al., 2001). Gupta et al (2004), however argued that the high productivity event at 10-8 Myr, which is considered to be the indicator of Asian monsoon onset, might have been the result of strengthening of the winds in response to global cooling and expanded Antarctic ice sheets, and not the uplift of Himalaya-Tibetan plateau leading to the enhanced nutrient delivery and upwelling, as similar high productivity events have also been reported from the Atlantic as well as the Pacific Ocean. A monsoon circulation system similar to that of today, with strong summer and winter seasonality had established by ~2.8 Ma, as inferred from the increased abundance of benthic foraminifera indicative of seasonal food supply (Gupta and Thomas, 2003).

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

The Quaternary period is marked by a large latitudinal change/redistribution in incoming solar radiation, the primary source of energy on earth. Such insolation changes are cyclic with a periodicity of 100 ka, 41 ka and 23 ka, and are collectively defined as Milankovitch cycles (Hays et al., 1976). As the solar

radiation received on earth drives a multitude of physical processes, efforts have also been made to understand the effect of Milankovitch scale changes in solar radiation received on earth on the monsoon intensity. A strong summer monsoon at obliquity maxima and 125° (8 kyrs) after precession minima was inferred from a compilation of marine and terrestrial proxy monsoon records (Clemens et al., 2010). Long-term records suggest distinct glacial-interglacial variability in monsoon intensity throughout the Pleistocene (Clemens and Prell, 1991). Out of several glacial-interglacial cycles, the monsoon intensity during the last glacial-interglacial transition has been reconstructed extensively, as such records can be easily retrieved in short gravity cores (<6 m length) from the continental shelf region as well as from the lakes. Several proxy records from both the Arabian Sea as well as Bay of Bengal suggest weakening of summer monsoon accompanied with possible intensification of winter monsoon during glacial times (Duplessy, 1982; Jain and Tandon, 2003; Dahl and Oppo, 2006; Banakar et al., 2010; Govil and Naidu, 2011; Saraswat et al., 2013) (Figure 2). The last deglaciation was marked by a weak monsoon interval interrupted by a short-lived phase of intense monsoon (Saraswat et al., 2013). The summer monsoon precipitation was however higher during the Bølling-Allerød as compared to the Younger Dryas and last glacial period possibly in response to changes in North Atlantic climate (Sinha et al., 2005; Rashid et al., 2007). A strong link between high latitude processes and monsoon in the Indian subcontinent and adjacent regions, with distinct Dansgaard-Oeschger cycles during the last glacial cycle, was inferred from high-resolution total organic carbon (a proxy for past productivity, which is linked to monsoon intensity) and surface dwelling planktic foraminiferal $\delta^{18}\text{O}$ records (Schulz et al., 1998; Kudrass et al., 2001). A comparison of such high resolution monsoon records with tropical and high latitude physical processes suggests a strong link between northern hemispheric climate and the monsoon on millennial time scales (Kudrass et al., 2001; Ivanochko et al., 2005). Additionally, ice core records from the tropical regions also provide strong evidence for a significant control of tropical hydrological cycle on changes in global atmospheric CH_4 concentration (Thompson et al., 2006).

D. Monsoon Changes during the Holocene

A summer monsoon optimum during the early Holocene was followed by a fluctuating summer monsoon intensity throughout most of the Holocene, as inferred from both the marine as well as terrestrial records (Gupta et al., 2003; Sharma et al., 2004; Rashid et al., 2007). The centennial-scale monsoon records also indicate strong links between the summer monsoon and north Atlantic climate

with weak summer monsoon coinciding with the North Atlantic cold periods throughout the Holocene including the most recent climate changes from the Medieval Warm Period to the Little Ice Age (Gupta et al., 2003; Kotlia et al., 2012). High resolution monsoon records revealed a significant shift in the monsoon at 4.2 ka BP which coincided with south-eastward migration of Harappan civilization settlements in the Indus valley accompanied by a change in living habitats from a highly organized urban phase to a phase of smaller settlements (Staubwasser et al., 2003). The annual to sub-annual scale changes in the monsoon during the past several thousand years have been inferred from tree rings (Yadav, 2013), speleothems (Burns et al., 2002; Sinha et al., 2005; Fleitmann et al., 2007; Kotlia et al., 2012) and corals (D'Arrigo et al., 2006; Gong and Luterbacher, 2008; Ahmad et al., 2011). Both short and long-term regular cyclic changes with a frequency varying from a few decades to a couple of millennia in the monsoon intensity have been inferred from both marine and terrestrial records (Naidu and Malmgren, 1995; Nigam et al., 1995; Agnihotri et al., 2002; Tiwari et al., 2005; Yadava and Ramesh, 2007; Rana and Nigam, 2009; Panchang and Nigam, 2012). A strong correlation between summer monsoon winds inferred from foraminiferal proxies and sunspot numbers clearly suggests that even small (<1%) decadal to centennial scale changes in insolation can bring pronounced changes in the tropical monsoon (Agnihotri et al., 2002; Gupta et al., 2005).

E. Quantitative Estimation of Paleomonsoon

As precipitation-evaporation over the sea as well as change in riverine influx in response to precipitation on land, directly controls seawater salinity in both the Bay of Bengal and Arabian Sea, it is a good estimate of past monsoon intensity. Thus, quantitative estimates of past seawater salinity calculated by correcting the stable oxygen isotopic ratio of the surface dwelling planktic foraminifera for global ice volume contribution and sea surface temperature estimated either from the Mg/Ca ratio in the same species (Saraswat et al., 2005; Dahl and Oppo, 2006; Rashid et al., 2007; Anand et al., 2008; Banakar et al., 2010; Govil and Naidu, 2011; Saraswat et al., 2012; 2013) or alkenone unsaturation ratio (Rostek et al., 1993; Saher et al., 2009), better constrains paleomonsoon changes. Additionally, a change in surface runoff as estimated from Ba/Ca ratio of surface dwelling planktic foraminifera is also a good proxy for past monsoon intensity (Saraswat et al., 2013). The surface salinity during the last glacial maximum was higher by ~2 practical salinity units (psu) in the northern Bay of Bengal (Kudrass et al., 2001), ~2.5 psu in the equatorial Indian Ocean (Rostek et al., 1993) and ~1 psu in the Bay of Bengal as compared to the

Holocene (Cullen, 1981), which implies a decreased summer monsoon. The surface seawater salinity of the equatorial Indian Ocean during penultimate interglacial period was ~1 psu lower as compared to the Holocene, suggesting excess of precipitation over evaporation (Rostek et al., 1993). A strong spatial variation in surface salinity during the LGM as compared to the Holocene with a non-uniform change in salinity over the northern Indian Ocean, suggesting differing summer and winter monsoon intensity has been inferred by several workers (Duplessy, 1982; Rostek et al., 1993; Dahl and Oppo, 2006; Anand et al., 2008). Such absolute salinity estimates, however have large associated uncertainty and should be viewed with caution. In addition to the application of seawater salinity as a proxy for quantitative reconstruction of past monsoon, tree rings are also used to estimate high resolution changes in precipitation (Yadav, 2013). Most of the tree-ring based past precipitation records, however are restricted to the Late Holocene.

An Overview of Articles in this Issue

In this special issue we present a total of six articles, out of which two are based on terrestrial records, one is a record from mud flats, and three are records from the Indian Ocean. The three records from the Indian Ocean, are respectively from the Bay of Bengal, the equatorial Indian Ocean and the Arabian Sea. Thus the records cover all the major sub-basins of the Indian Ocean as well as the terrestrial archives. Such a comprehensive collection of monsoon records generated by using different proxies from various archives will help to understand the factors that control monsoon changes in the Indian subcontinent and nearby oceanic regions and further, the role of tropical monsoon changes in global climatic variations.

Sarkar and Gupta (2013) reconstruct high resolution equatorial processes between ~450-150 Kyr from productivity changes by using benthic foraminiferal assemblages from the Ocean Drilling Program (ODP) Hole 716A drilled near the Maldives ridge. A transition from relatively high organic flux accumulation combined with low oxygen condition to seasonal organic flux and high dissolved oxygen condition is inferred during the mid-Brunhes climatic transition. Mahesh and Banakar (2013) apply paired measurement of $\delta^{18}\text{O}$ and trace metal ratio (Mg/Ca) in surface dwelling planktic foraminifera *Globigerinoides sacculifer* in two cores collected along a north-south transect and covering a time span back to the last glacial period to assess absolute sea surface salinity changes in the eastern Arabian Sea. They suggest decreased summer monsoon intensity leading to low fresh water discharge in

the Bay of Bengal combined with intense winter monsoon as the cause of the increased north-south salinity gradient during the last glacial period. Tripathy et al (2013) use major and trace element analysis of sediments from a piston core collected from the western Bay of Bengal, to constrain climate driven changes in provenance over the last glacial-interglacial period. A significant reduction in the contribution of sediments by the Himalayan rivers as compared to the Peninsular rivers is inferred during the last glacial period, possibly due to reduction in southwest monsoon strength as well as area exposed to erosion with increased ice cover in the Himalayas. Prasad et al (2013) report the findings of a multi-proxy study involving palynology, phytoliths, sedimentology, clay mineralogy, carbon isotopes and magnetic mineralogy on a core collected from Wadhvana Lake in Gujarat, India to understand the mid-Holocene climatic changes in this region and its role in modulating the Harappan culture. A beginning of dry climate is inferred at ~5500 cal yr BP which possibly lead to the urbanization in Harappan civilization in North West India whereas a later excessive dry phase at ~4200-4255 cal yr BP forced the decline of the Harappan civilization. Warriar et al (2013) use sedimentological and carbonate data to corroborate application of rock magnetic properties for paleomonsoon studies as well as to understand past monsoon intensity from a core collected from the Thimmannanayakanakere lake located at the foothills of the Chitradurga Fort, Karnataka. Based on this work, the authors infer low lake level, possibly due to arid conditions between 3.7 cal. ka B.P. to ~2 cal. ka B.P., sub-humid condition between 2 cal. ka B.P. to ~1 cal. ka B.P., and humid condition From 1 cal. ka B.P. to the present leading to sharp rise in lake level. The authors suggest that χ_{lf} can be used as a proxy for tropical rainfall. Tomchou et al (2013) use major and trace metals, mineralogy, grain size and radionuclide (^{210}Pb) analyses to understand past environmental changes from the sediment cores collected from mudflat regions of central west coast of India. A significant shift in sediment characteristics is observed post 1980, probably in response to changes in climatic conditions mainly driven by the monsoon.

Lack of High Resolution Quantitative Paleomonsoon Records

The origin and long-term evolution of the monsoon has been well documented by several workers, as discussed briefly above, including the articles published in this special issue. The high resolution centennial to sub-centennial scale records of qualitative changes in past monsoon have also been reconstructed from both the Arabian Sea and Bay of Bengal (Schulz et al., 1998; Kudrass et al., 2001), as well as from the Indian subcontinent (Ramesh et al., 1985; Sinha et al., 2005; Yadav, 2013). The

continuous quantitative estimates of paleomonsoon intensity (based on seawater $\delta^{18}\text{O}$) covering the last glacial-interglacial transition, however are limited and have coarse resolution with each sample representing a couple of centuries or more, except a few records that have centennial resolution and cover a part of the last glacial as well as the full termination I (Saher et al., 2007; Saraswat et al., 2013). The centennial or sub-centennial scale quantitative records of paleomonsoon (paleosalinity) and temperature over the glacial-interglacial terminations are required to assess the link between low and high latitude processes, such as the initiation of deglacial warming during the terminations and timing of change in monsoon intensity. Such records will further help to infer the lead-lag relationship, if any, between monsoon and other regional as well as global climate processes, including El-Nino Southern Oscillation, Indian Ocean Dipole, Walker Circulation, Madden-Julian Oscillation. The regions with very high sedimentation like the northern Bay of Bengal, in front of the major rivers such as Irrawaddy, Ganga-Brahmaputra, Mahanadi, as well as the northern Arabian Sea (Indus Fan region) and selected lakes should be targeted to collect good quality cores. These regions however are not only prone to slump resulting in turbidite sequences, but also have very small percentage of biogenic carbonates, thus making it difficult to apply calcareous fossil based proxies to reconstruct past monsoon changes, in cores collected from such regions. Application of recently developed proxies for quantitative estimation of climatic parameters (Tetraether index TEX_{86} , carbonate clumped isotope, hydrogen isotopic composition of plant leaf-wax n-alkanes $\delta\text{D}_{\text{wax}}$) on such cores will help in reconstructing high resolution quantitative estimates of past monsoon intensity. Additionally, efforts should be made to develop robust proxies to estimate quantitative changes in past monsoon intensity from both the marine and terrestrial records.

Acknowledgements

We are thankful to Dr. V. Ramaswamy of the National Institute of Oceanography, Goa, for accepting our proposal to convene a session on the Quaternary monsoon history in the Seventh International Conference on Asian Marine Geology. We express our sincere thanks to all those who contributed abstracts to the session. We acknowledge the cooperation of all the authors of the articles published in this special issue. We are grateful to all the reviewers for spending their valuable time to review the manuscripts and suggest changes that helped to improve the manuscripts. We would like to acknowledge the help of the technical staff of the journal for processing the manuscripts.

References

- Agnihotri, R., Dutta, K., Bhushan, R., Somayajulu, B.L.K., 2002. Evidence for solar forcing on the Indian monsoon during the last millennium. *Earth and Planetary Science Letters* 198, 521-527.
- Ahmad, S.M., Padmakumari, V.M., Raza, W., Venkatesham, K., Suseela, G., Sagar, N., Chamoli, A., Rajan, R.S., 2011. High-resolution carbon and oxygen isotope records from a scleractinian (*Porites*) coral of Lakshadweep Archipelago. *Quaternary International* 238, 107-114.
- Almogi-Labin, A., Hemleben, C., Meischner, D., Erlenkeuser, H., 1991. Paleoenvironmental events during the last 13,000 years in the central Red Sea as recorded by pteropoda. *Paleoceanography* 6, 83-98.
- Altabet, M.A., Higginson, M.J., Murray, D.W., 2002. The effect of millennial-scale changes in Arabian Sea denitrification on atmospheric CO₂. *Nature* 415, 159-162.
- An, Z., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalayan–Tibetan Plateau since Late Miocene times. *Nature*, 411, 62–66.
- An, Z., Clemens, S. C., Shen, J., Qiang, X., Jin, Z., Sun, Y., Prell, W. L., Luo, J., Wang, S., Xu, H., Cai, Y., Zhou, W., Liu, X., Liu, W., Shi, Z., Yan, L., Xiao, X., Chang, H., Wu, F., Ai, L., Lu, F., 2011. Glacial-interglacial Indian summer monsoon dynamics. *Science*, 333, 719-723.
- Anand, P., Kroon, D., Singh, A.D., Ganeshram, R.S., Ganssen, G., Elderfield, H., 2008. Coupled sea surface temperature seawater $\delta^{18}\text{O}$ reconstructions in the Arabian Sea at the millennial scale for the last 35 ka. *Paleoceanography* 23, PA4207. doi:10.1029/2007PA001564.
- Ashok, K., Guan, Z., Saji, N.H., Yamagata, T., 2004. On the individual and combined influences of the ENSO and the Indian Ocean dipole on the Indian summer monsoon. *Journal of Climate* 17, 3141-3154.
- Banakar, V.K., Mahesh, B.S., Burr, G., Chodankar, A.R., 2010. Climatology of the Eastern Arabian Sea during the last glacial cycle reconstructed from paired measurement of foraminiferal $\delta^{18}\text{O}$ and Mg/Ca. *Quaternary Research* 73, 535-540.
- Blanford, H.F., 1884. On the connection of the Himalayan snowfall with dry winds and seasons of draughts in India. *Proceedings of the Royal Society, London*, 37, 3-22.
- Böning, P., Bard, E., 2009. Millennial/centennial-scale thermocline ventilation changes in the Indian Ocean as reflected by aragonite preservation and geochemical variations in Arabian Sea sediments. *Geochimica et Cosmochimica Acta* 73, 6771-6788.
- Burns, S. J., Fleitmann, D., Mudelsee, M., Neff, U., Matter, A., Mangini, A., 2002. A 780-year annually resolved record of Indian Ocean monsoon precipitation from a speleothem from south Oman. *Journal of Geophysical Research* 107, 4434, doi:10.1029/2001JD001281.

- Caley, T., Malaizé, B., Zaragosi, S., Rossignol, L., Bourget, J., Eynaud, F., Martinez, P., Giraudeau, J., Charlier, K., Zimmermann, N.E., 2011. New Arabian Sea records help decipher orbital timing of Indo-Asian monsoon. *Earth and Planetary Science Letters* 308, 433-444.
- Chakraborty, A., Nanjundiah, R. S., Srinivasan, J., 2002. Role of Asian and African orography in Indian summer monsoon. *Geophysical Research Letters*, 29, doi:10.1029/2002GL015522,.
- Charney, J.G., 1969. The intertropical convergence zone and the hadley circulation of the atmosphere. *Proc. WMO/IUCG Symp. Numer. Weather Predict. Jpn. Meteorol. Agency III*, 73-79.
- Chauhan, O.S., Sukhija, B.S., Gujar, A.R., Nagabhushanam, P., Paropkari, A.L., 2000. Late-Quaternary variations in clay minerals along the SW continental margin of India: Evidence of climatic variations. *Geo-Marine Letters* 20, 118-122.
- Clemens, S.C., Prell, W.L., 1991. One-million year record of summer-monsoon winds and continental aridity from the Owen Ridge (Site 722B), northwest Arabian Sea. *Ocean Drill. Prog. Sci. Res.* 117, 365-388.
- Clemens, S.C., Prell, W.L., Sun, Y., 2010. Orbital-scale timing and mechanisms driving Late Pleistocene Indo-Asian summer monsoons: Reinterpreting cave speleothem $\delta^{18}\text{O}$. *Paleoceanography*, 25, PA4207, doi:10.1029/2010PA001926.
- Clift, P.D., Plumb, R.A., 2008. *The Asian Monsoon: Causes, History and Effects*, Cambridge University Press, pp. 270, ISBN 978-0-521-84799-5.
- Cullen, J.L., 1981. Microfossil evidence for changing salinity patterns in the Bay of Bengal over the last 20,000 years. *Palaeogeography Palaeoclimatology Palaeoecology* 35, 315-356.
- Dahl, A.K., Oppo, D.W., 2006. Sea surface temperature pattern reconstructions in the Arabian Sea. *Paleoceanography* 21, PA1014. doi:10.1029/2005PA001162.
- D'Arrigo, R., Wilson, R., Palmer, J., Krusic, P., Curtis, A., Sakulich, J., Bijaksana, S., Zulaikah, S., Ngkoimani, L.O., Tudhope, A., 2006. The reconstructed Indonesian warm pool sea surface temperatures from tree rings and corals: Linkages to Asian monsoon drought and El Nino-Southern Oscillation. *Paleoceanography*, 21, PA3005.
- Duplessy, J.C., 1982. Glacial to interglacial contrasts in the northern Indian Ocean. *Nature* 295, 494-498.
- Fleitmann, D., Burns, S. J., Mangini, A., Mudelsee, M., Kramers, J., Neff, U., Al-Subbary, A. A., Matter, A., 2007. Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). *Quaternary Science Reviews* 26, 170-188.
- Flohn, H. 1968. *Contributions to a meteorology of the Tibetan Highlands*. Atmospheric Science Paper Number 130, Colorado State University, 120.

- Gadgil, S., 2003. The Indian monsoon and its variability. *Annual Reviews of Earth and Planetary Science* 31, 429-467.
- Gadgil S., Vinayachandran, P.N., Francis, P.A., Gadgil, S., 2004. Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. *Geophysical Research Letters* 31, L12213.
- Gong, D.-Y., Luterbacher, J., 2008. Variability of the low-level cross-equatorial jet of the western Indian Ocean since 1660 as derived from coral proxies. *Geophysical Research Letters* 35, L01705.
- Govil, P., Naidu, P.D., 2011. Variations of Indian monsoon precipitation during the last 32 kyr reflected in the surface hydrography of the Western Bay of Bengal. *Quaternary Science Reviews* 30, 3871-3879.
- Gupta, A.K., Thomas, E., 2003. Initiation of Northern hemisphere glaciation and strengthening of the northeast Indian monsoon: ocean drilling program site 758, eastern equatorial Indian Ocean. *Geology* 31, 47-50.
- Gupta, A.K., Anderson, D.M., Overpeck, J.T., 2003. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. *Nature* 421, 354-357.
- Gupta, A.K., Singh, R.K., Joseph, S., Thomas, E., 2004. Indian Ocean high-productivity event (10–8 Ma): linked to global cooling or to the initiation of the Indian monsoons? *Geology* 32, 753-756.
- Gupta, A.K., Das, M., Anderson, D. M., 2005. Solar influence on the Indian summer monsoon during the Holocene. *Geophysical Research Letters*, 32, L17703, doi:10.1029/2005GL022685.
- Gupta, S.M., 2003. Orbital frequencies in radiolarian assemblages of the central Indian Ocean: implications on the Indian summer monsoon. *Palaeogeography Palaeoclimatology Palaeoecology* 197, 1-16.
- Hahn, D.G., Manabe, S., 1975. The role of mountains in the south Asian monsoon circulation. *Journal of Atmospheric Science*, 32, 1515-1541.
- Hays, J. D., Imbrie, J., Shackleton, N. J., 1976. Variations in the Earth's orbit: Pacemaker of the Ice Ages. *Science* 194, 1121-1132.
- Heinz, P., Hemleben, C., 2006 Foraminiferal response to the Northeast Monsoon in the western and southern Arabian Sea. *Marine Micropaleontology* 58, 103-113.
- Hong, Y.T., Hong, B., Lin, Q.H. Shibata, Y., Hirota, M., Zhu, Y.X., Leng, X.T., Wang, Y., Wang, H. and Yi, L., 2005. Inverse phase oscillations between the East Asian and Indian Ocean summer monsoons during the last 12000 years and paleo- El Niño. *Earth and Planetary Science and Letters*, 231, 337-346.
- Ihara, C., Kushnir, Y., Cane, M.A., Pena, V.H.D.L., 2007 Indian summer monsoon rainfall and its link with ENSO and Indian Ocean climate indices. *International Journal of Climatology* 27, 179-187.

- Ivanochko, T.S., Ganeshram, R.S., Brummer, G.-J. A., Ganssen, G., Jung, S.J.A., Moreton, S.G., Kroon, D., 2005. Variations in tropical convection as an amplifier of global climate change at the millennial scale. *Earth and Planetary Science Letters* 235, 302-314.
- Jain, M., Tandon, S.K., 2003. Fluvial response to Late Quaternary climatic changes, Western India. *Quaternary Science Reviews*, 33, 2223-2235.
- Kessarkar, P.M., Rao, V.P., Ahmad, S.M., Patil, S.K., AnilKumar, A., AnilBabu, G., Chakraborty, S., SounderRajan, R., 2005. Changing sedimentary environment during the late Quaternary: Sedimentological and isotopic evidence from the distal Bengal Fan. *Deep-Sea Research I: Oceanographic Research Papers* 52, 1591-1615.
- Kotlia, B. S., Ahmad, S. M., Zhao, J.-X., Raza, W., Collerson, K. D., Joshi, L. M., Sanwal, J., 2012. Climatic fluctuations during the LIA and post-LIA in the Kumaun Lesser Himalaya, India: Evidence from a 400 y old stalagmite record. *Quaternary International* 263, 129-138.
- Kripalani, R.H., Kumar, P., 2004. Northeast monsoon rainfall variability over south peninsular India vis-a-vis the Indian Ocean dipole mode. *International Journal of Climatology* 24, 1267-1282.
- Krishnamurthy, V., Kirtman, B.P., 2003. Variability of the Indian Ocean: Relation to monsoon and ENSO. *Quaternary Journal of Royal Meteorological Society* 129, 1623-1646.
- Krishna Kumar, K., Rajagopalan B., Cane, M.A., 1999. On the weakening relationship between the Indian monsoon and ENSO. *Science* 287, 2156-2159.
- Kroon, D., Steens, T., Troelstra, S. R., 1991. Onset of monsoon related upwelling in the western Arabian Sea as revealed by planktonic foraminifers. *Proceedings of Ocean Drilling Program Scientific Results* 117, 257-263.
- Kudrass, H.R., Hofmann, A., Doose, H., Emeis, K., Erlenkeuser, H., 2001. Modulation and amplification of climatic changes in the Northern Hemisphere by the Indian summer monsoon during the past 80 k.y. *Geology* 29, 63-66
- Lau, N.-C., Nath, M.J., 2000. Impact of ENSO on the variability of the Asian-Australian Monsoons as simulated in GCM experiments. *Journal of Climate* 13, 4287-4309.
- Li, T., Zhang, Y., Chang, C.-P., Wang, B., 2001. On the Relationship between Indian Ocean Temperature and Asian Summer Monsoon. *Geophysical Research Letters* 28, 2843-2846.
- Naidu, P.D., Malmgren, B.A., 1995. A 2,200 years periodicity in the Asian Monsoon system. *Geophysical Research Letters* 22, 2361-2364.
- Naik, S.S., Naidu, P.D., Govil, P., Godad, S.P., 2010. Relationship between weights of planktonic foraminifer shell and surface water CO₃⁻ concentration during the Holocene and Last Glacial Period. *Marine Geology* 275, 278-282.

- Nigam, R., Khare, N., Nair, R.R., 1995. Foraminiferal evidences for 77-year cycles of droughts in India and its possible modulation by the Gleissberg solar cycle. *Journal of Coastal Research* 11, 1099-1107.
- Panchang, R., Nigam, R. 2012. High resolution climatic records of the past ~489 years from Central Asia as derived from benthic foraminiferal species, *Asterorotalia trispinosa*. *Marine Geology* 307-310, 88-104.
- Prabhu, C.N., Shankar, R., Anupama, K., Taieb, M., Bonnefille, R., Vidal, L., Prasad, S., 2004. A 200-ka pollen and oxygen-isotopic record from two sediment cores from the eastern Arabian Sea. *Palaeogeography, Palaeoclimatology, Palaeoecology* 214, 309-321.
- Prasad, S., Kusumgar, S., Gupta, S.K., 1997. A mid-late Holocene record of palaeoclimatic changes from Nal Sarovar-a palaeodesert margin lake in western India. *Journal of Quaternary Science* 12, 153-159.
- Prell, W.L., Campo, E.V., 1986. Coherent response of Arabian Sea upwelling and pollen transport to late Quaternary monsoonal winds. *Nature* 323, 526-528.
- Prell, W.L., Murray, D.W., Clemens, S.C., Anderson, D.M., 1992. Evolution and variability of the Indian Ocean summer monsoon: Evidence from the western Arabian sea drilling program, in *Synthesis of Results From Scientific Drilling in the Indian Ocean*, Geophys. Monogr. Ser., vol. 70, edited by R. A. Duncan et al., pp. 447-469, AGU, Washington, D. C.
- Rana, S.S., Nigam, R., 2009. Cyclicity in the Late Holocene monsoonal changes from the western Bay of Bengal: Foraminiferal approach. *Journal of Palaeontological Society of India* 54, 165-170.
- Rao, V.P., Kessarkar, P.M., Thamban, M., Patil, S.K., 2010. Paleoclimatic and diagenetic history of the Late Quaternary sediments in a core from the southeastern Arabian Sea: Geochemical and magnetic signals. *Journal of Oceanography* 66, 133-146.
- Ramesh, R., Bhattacharya, S.K., Gopalan, K., 1985. Dendroclimatological implications of isotope coherence in trees from Kashmir Valley, India. *Nature*, 317, 802-804.
- Rashid, H., Flower, B.P., Poore, R.Z., Quinn, T.M., 2007. A ~25 ka Indian Ocean monsoon variability record from the Andaman Sea. *Quaternary Science Reviews* 26, 2586-2597.
- Rasmusson, E.M., Carpenter, T.H., 1983. The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. *Monthly Weather Review* 111, 517-528.
- Rostek, F., Ruhland, G., Bassinot, F.C., Muller, P.J., Labeyrie, L.D., Lancelot, Y., Bard, E., 1993. Reconstructing sea surface temperature and salinity using $\delta^{18}\text{O}$ and alkenone records. *Nature* 364, 319-321.
- Saher, M. H., Peeters, F. J. C., Kroon, D., 2007. Sea surface temperatures during the SW and NE monsoon seasons in the western Arabian Sea over the past 20,000 years. *Palaeogeography Palaeoclimatology Palaeoecology* 249, 216-228.

- Saher, M.H., Rostek, F., Jung, S.J.A., Bard, E., Schneider, R.R., Greaves, M., Ganssen, G.M., Elderfield, H., Kroon, D., 2009. Western Arabian Sea SST during the penultimate interglacial: a comparison of U37K and Mg/Ca paleothermometry. *Paleoceanography* 24, PA2212. doi:10.1029/2007PA001557.
- Saraswat, R., Nigam, R., Weldeab, S., Mackensen, A., Naidu, P.D., 2005. A first look at past sea surface temperatures in the equatorial Indian Ocean from Mg/Ca in foraminifera. *Geophysical Research Letters* 32, doi:10.1029/2005GL024093.
- Saraswat, R., Nigam, R., Mackensen, A., Weldeab, S., 2012. Linkage between seasonal insolation gradient in the tropical northern hemisphere and the sea surface salinity of the equatorial Indian Ocean during the last glacial period. *Acta Geologica Sinica* 86, 1265-1275.
- Saraswat, R., Lea, D.W., Nigam, R., Mackensen, A., Naik, D.K., 2013. Deglaciation in the tropical Indian Ocean driven by interplay between the regional monsoon and global teleconnections. *Earth and Planetary Science Letters* 375, 166-175.
- Schulz, H., von Rad, U., Erlenkeuser, H., 1998. Correlation between Arabian Sea and Greenland climate oscillations of the past 110 000 years. *Nature* 393, 54-57.
- Sharma, S., Joachimski, M., Sharma, M., Tobschall, H.J., Singh, I.B., Sharma, C., Chauhan, M.S., Morgenroth, G., 2004. Late glacial and Holocene environmental changes in Ganga plain, Northern India. *Quaternary Science Reviews* 23, 145-159.
- Sijinkumar, A.V., Nath, B.N., Gupta, M.V.S., 2010. Late Quaternary record of pteropod preservation from the Andaman Sea. *Marine Geology* 275, 221-229.
- Simpson G. 1921. The south-west monsoon. *Quaternary Journal of the Royal Meteorological Society*, 199, 150-73.
- Singhvi, A.K., Bluszcz, A., Bateman, M.D., Rao, M. S., 2001. Luminescence dating of loess-palaeosol sequences and coversands: methodological aspects and palaeoclimatic implications. *Earth-Science Reviews*, 54, 193-211.
- Sinha, A., Cannariato, K.G., Stott, L.D., Li, H.C., You, C.F., Cheng, H., Edwards, R.L., Singh, I.B., 2005. Variability of southwest Indian summer monsoon precipitation during the Bølling-Ållerød. *Geology*, 33, 813-816.
- Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M., Duplessy, J.C., 1993. Century-scale events in monsoonal climate over the past 24,000 years. *Nature* 364, 322-324.
- Sirocko, F., Schonberg, D.G., Devey, C., 2000. Processes controlling trace element geochemistry of Arabian Sea sediments during the last 25,000 years. *Global and Planetary Change* 26, 217-303.
- Staubwasser, M., Sirocko, F., Grootes, P.M., Segl, M., 2003. Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability. *Geophysical Research Letters*, 30, 1425.

- Sukumar, R., Ramesh, R., Pant, R.K., Rajagopalan, G., 1993. A $\delta^{13}\text{C}$ record of late Quaternary climate change from tropical peats in southern India. *Nature* 364, 703-706
- Thamban, M., Rao, V.P., Schneider, R.R., 2002. Reconstruction of late Quaternary monsoon oscillations based on clay mineral proxies using sediment cores from the western margin of India. *Marine Geology* 186, 527-539.
- Thompson, L.G., Yao, T., Davis, M.E., Henderson, K.A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.-A., Cole-Dai, J., Bolzan, J.F., 1997. Tropical climate instability: the Last Glacial Cycle from a Qinghai-Tibetan Ice Core. *Science* 276, 1821-1827.
- Thompson, L.G., Thompson, E.M., Davis, M.E., Mashiotta, T.A., Henderson, K.A., Lin, P., Yao, T., 2006. Ice core evidence for asynchronous glaciation on the Tibetan Plateau. *Quaternary International* 154-155, 3-10.
- Tiwari, M., Ramesh, R., Somayajulu, B.L.K., Jull, A.J.T., Burr, G.S., 2005. Solar control of southwest monsoon on centennial timescales. *Current Science* 89, 1583-1588.
- Tripathy, G.R., Singh, S.K., Bhushan, R., Ramaswamy, V., 2011. Sr-Nd isotope composition of the Bay of Bengal sediments: Impact of climate on erosion in the Himalaya. *Geochemistry Journal* 45, 175-186.
- Wünnemann, B., Demske, D., Tarasov, P., Kotlia, B.S., Reinhardt, C., Bloemendal, J., Diekmann, B., Hartmann, K., Krois, J., Riedel, F., Arya, N., 2010. Hydrological evolution during the last 15 kyr in the Tso Kar lake basin (Ladakh, India), derived from geomorphological, sedimentological and palynological records. *Quaternary Science Reviews* 29, 1138-1155.
- Yadav, R. R., 2013. Tree ring-based seven-century drought records for the Western Himalaya, India. *Journal of Geophysical Research: Atmosphere* 118, doi:10.1002/jgrd.50265.
- Yadava, M.G., Ramesh, R., 2007. Significant longer-term periodicities in the proxy record of the Indian monsoon rainfall. *New Astronomy* 12, 544-555.
- Yang, J., Liu, Q., Xie, S.-P., Liu, Z., Wu, L., 2007. Impact of the Indian Ocean SST basin mode on the Asian summer monsoon. *Geophysical Research Letters* 34, L02708.
- Walker, G.T., 1910. On the meteorological evidence for supposed changes of climate in India. *Indian Meteorological Memoirs* 21, 1-21.

Legend to Figures

Figure 1: Average precipitation (mm/day) over the Indian subcontinent and the adjoining sea during the summer monsoon (June-September) (A), and winter monsoon season (November-February) (B). A prominent shift is observed in the rainfall belt from the northern tropical region during boreal summer towards the south during the winter (Source: las_server/LAS_Data/Global/Precipitation/TRMM_M.nc).

Figure 2: A few high resolution proxy paleomonsoon records covering the last glacial-interglacial transition, reconstructed from the northern Indian Ocean. NIOP929 $\delta^{18}\text{O}_{\text{sw}}$ (Saher et al., 2007); SK237 GC04 $\delta^{18}\text{O}_{\text{sw}}$ (Saraswat et al., 2013); 136KL total organic carbon (TOC) (Schulz et al., 1998); 126KL Salinity (Kudrass et al., 2001); RC27-14 $\delta^{15}\text{N}$ (Altabet et al., 2002). The salinity scale of 126KL is reversed so as to indicate high salinity (weak monsoon) towards the base.

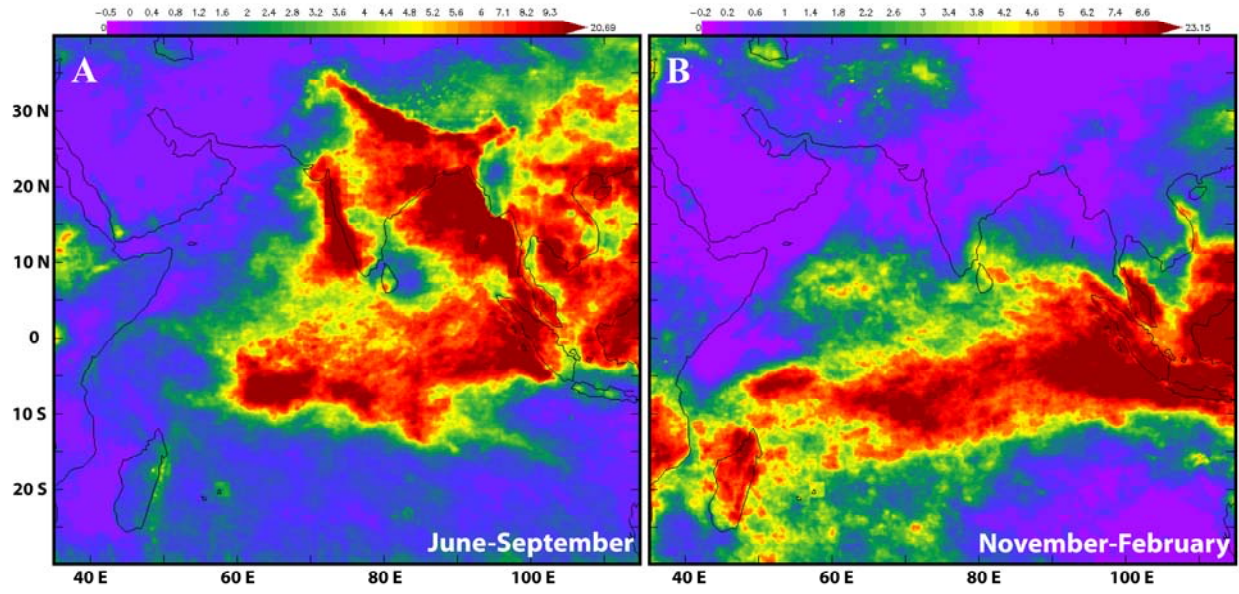


Figure 1: Average precipitation (mm/day) over the Indian subcontinent and the adjoining sea during the summer monsoon (June-September) (A), and winter monsoon season (November-February) (B). A prominent shift is observed in the rainfall belt from the northern tropical region during boreal summer towards the south during the winter (Source: [las_server/LAS_Data/Global/Precipitation/TRMM_M.nc](#)).

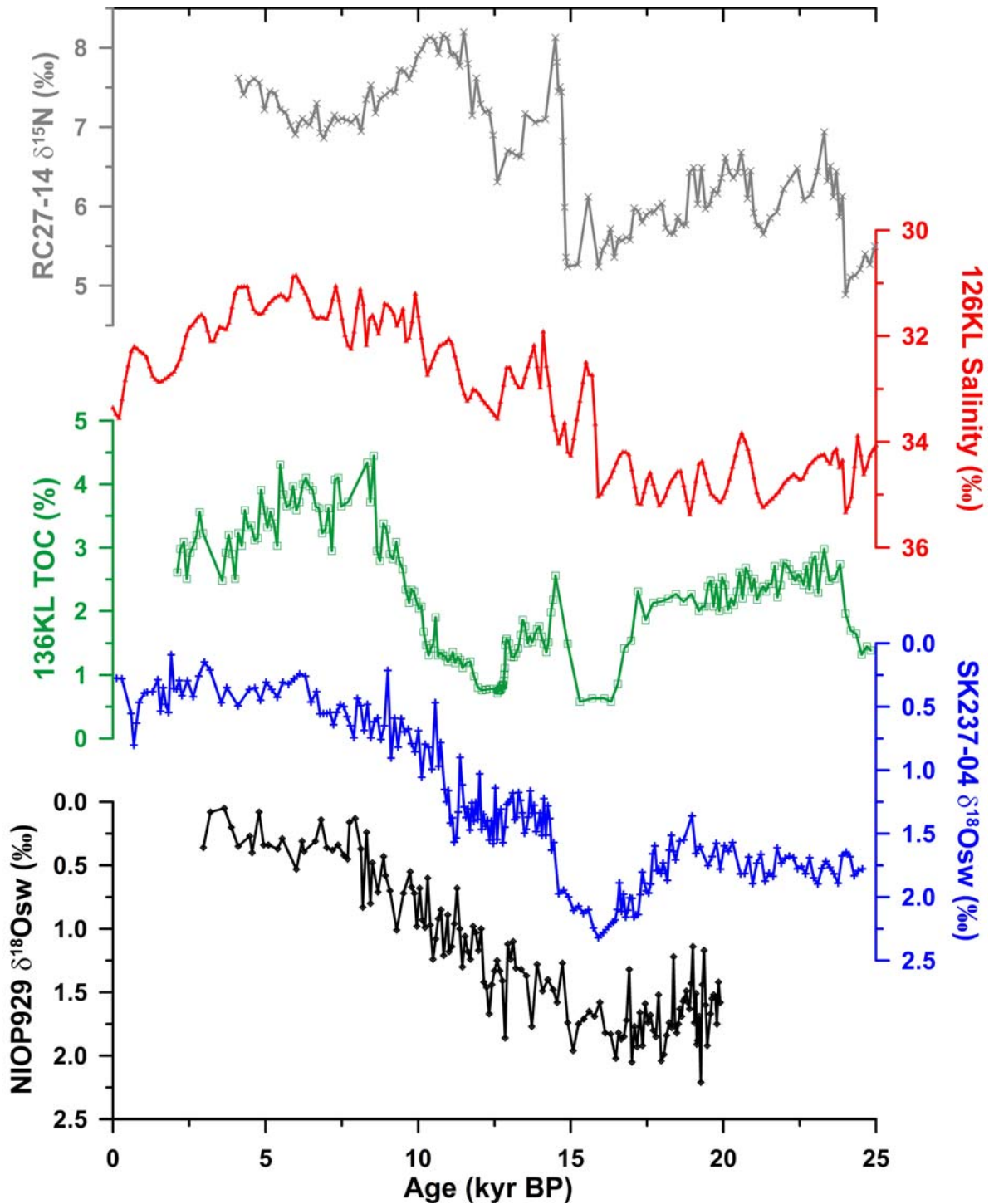


Figure 2: A few high resolution proxy paleomonsoon records covering the last glacial-interglacial transition, reconstructed from the northern Indian Ocean. NIOP929 $\delta^{18}\text{Osw}$ (Saher et al., 2007); SK237 GC04 $\delta^{18}\text{Osw}$ (Saraswat et al., 2013); 136KL total organic carbon (TOC) (Schulz et al., 1998); 126KL Salinity (Kudrass et al., 2001); RC27-14 $\delta^{15}\text{N}$ (Altabet et al., 2002). The salinity scale of 126KL is reversed so as to indicate high salinity (weak monsoon) towards the base.