Synopsis of the Ph.D. thesis entitled

Palaeoclimatic reconstructions based on marine sediments from the Northern Indian Ocean: Implications to Aeolian flux and Productivity

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Introduction

Marine sediments offer a significant and comprehensive archive of Earth's climatic history (deMenocal, 2014) and also records the past changes in the surface productivity, hydrography and climate over the surrounding land mass. Marine archives are mostly continuous temporal records with its resolution being influenced by the rate of sedimentation. The marine sedimens from the Arabian Sea have been under focus from many Palaeoceanographers and Palaeoclimatologists in the recent decades due to the unique nature (ephemeral Oxygen minimum zone, riverine flux in east, aeolian flux in west, summer upwelling, winter mixing and seasonal productivity) of the basin. The surface water circulation in Arabian Sea is controlled by seasonal changes in atmospheric wind pattern related with annual migration of ITCZ (Wyrtki, 1973). During boreal winter, ITCZ stays south of equator and shifts to north during boreal summer. This northward shift of ITCZ during southwest monsoon (SWM, June-September) season drives the southern hemisphere eastern trade winds across equator that turns clockwise and becomes southwest winds (Findlater, 1978). These southwest winds help to form the Somali current along the east African coast towards north. The Somali current is generally associated with near shore upwelling and eddies such as southern gyre, great whirl and Soccotra eddy (Schott et al., 1990; Beal and Chereskin, 2003; Schott et al., 2009). These eddies induce intense upwelling which pumps out the low temperature and nutrient rich subsurface water to the surface along the east coast of Africa (Young and Kindle, 1994) and Arabian coast. Productivity in Arabian Sea reflects the seasonal changes in surface ocean characteristics (Qasim, 1977; Brock et al., 1991). More than half of the annual productivity in the Arabian Sea occurs during southwest monsoon due to intense upwelling (Haake et al., 1993). Total flux (biogenic + dust) also peaks at the same time when productivity is at its maximum, meaning that SWM not only causes high productivity in the Arabian Sea but also high dust flux (Sirocko and Lange, 1991; Haake et al., 1993). The southward shift of ITCZ during boreal winter brings cold and dry northeast monsoon winds (NEM). This NEM winds cause convective mixing and deepens the mixed layer depth in the northeast Arabian Sea. Convective mixing brings up the subsurface nutrients to euphotic zone and increases the surface productivity. How these processes have changed during the past and how the regional climate evolved through glacial-interglacial time scales has not been fully understood. The present study thus aims to reconstruct the glacial-interglacial scale variations in the palaeoclimate of Indian monsoon region using two sediment cores from the eastern and western part of Arabian Sea.

Research gaps

Marine records from Arabian Sea have suggested a strengthened southwest monsoon during the Holocene (Sirocko et al., 1993; Sarkar et al., 2000). However the palaeoclimate records from Indian subcontinent and west coast indicate a weakened southwest monsoon precipitation during the Holocene (Fleitmann et al, 2003; Anand et al., 2008; Govil and Naidu, 2010). A further study and understanding of the palaeoclimatic records therefore gains significance.

Moreover, the Northern Indian Ocean experiences high aeolian dust deposition from surrounding desert regions (Arabian and African deserts). The dust plays a major role in global climate directly through their influence on nutrient flux and thereby carbon sequestration in the oceans. The effect of dust flux on carbon export flux in the study area remains unexplored.

The surface productivity in Arabian Sea is modulated by upwelling, lateral advection and convective mixing. Most of the palaeo-productivity records are from the coastal regions of India and Arabia. The knowledge about the palaeo-productivity in open Arabian Sea is very limited and the influence of lateral advection of upwelled waters on the productivity at different time periods needs to be established.

Erosion of mountain belts is enforced by the interplay between high frequency climate change and low frequency tectonic activity. Tectonic activity dominant over million year time scale is considered to be the prime cause for Himalayan erosion with climate playing a secondary role. However, recent studies highlight the importance of climate in controlling erosion over shorter time scale. The relation between Himalayan erosion and terrigenous sediment flux to Northern Indian Ocean needs attention.

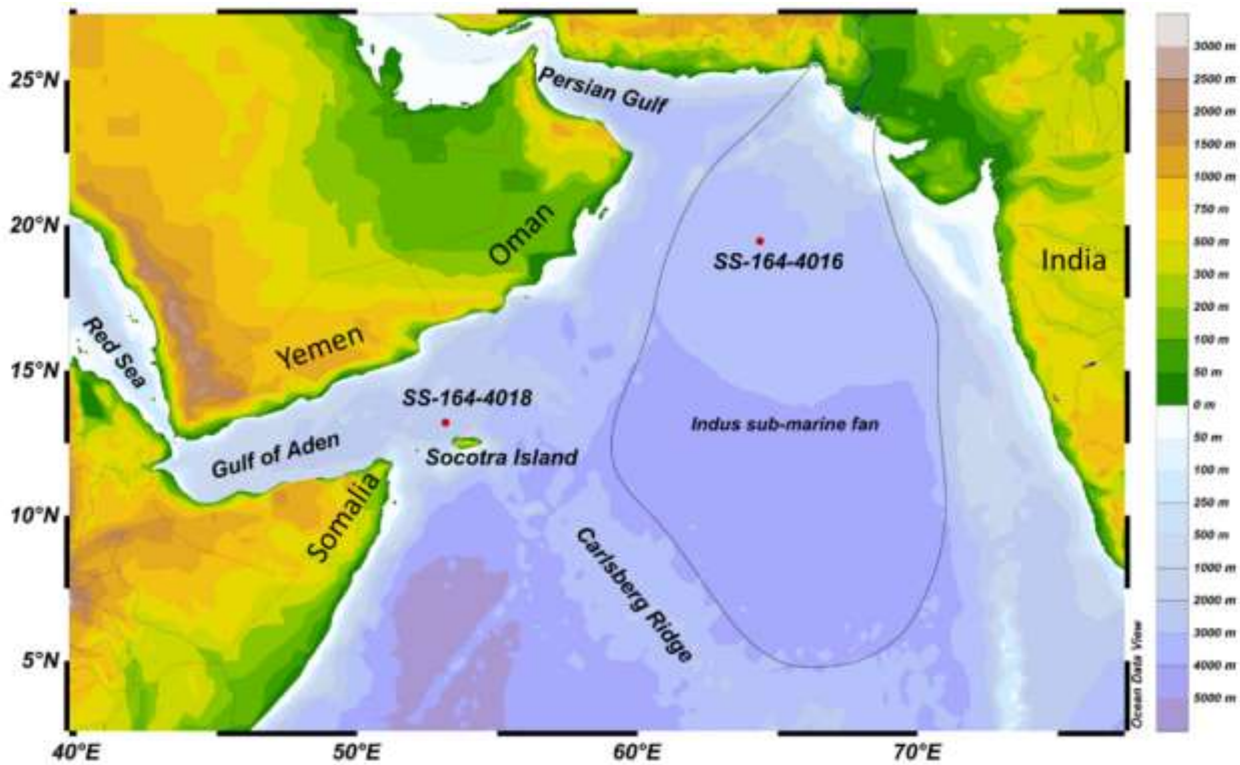
Objectives

1. To reconstruct the temporal variation of southwest monsoon using upwelling proxy. Try to find the reasons for the controversy between marine and terrestrial palaeoclimate records.

2. To understand the past variations in aeolian flux to the Northern Indian Ocean and its impact on carbon export flux.
3. To reconstruct the palaeo-productivity variations in the open Arabian sea and to establish the influence of lateral advection on palaeo-productivity.
4. To assess the role of climate in controlling Himalayan erosion by studying the terrigenous flux to northern Arabian Sea.

Methodology

Two marine sediment cores were raised from Arabian Sea; one core (4018) was retrieved from western part of the Sea near the Socotra Island and the other core (4016) was collected



from northern part (Figure 1). The 4018 sediment core location is influenced by the Somali upwelling during the southwest monsoon season. Hence the proxy variations in the 4018 sediment core can be used to reconstruct the history of Somali upwelling intensity as well as the southwest monsoon strength during the past. The open ocean condition at 4016 sediment core site would be helpful in deciphering the influence of monsoon on the biogeochemistry of open Arabian Sea. Both the sediment cores were sub-sampled at two centimeter interval onboard FORV-Sagar Sampada cruise.

Figure 1. Map of the study area in the Northern Indian Ocean. Red dots mark the location of the sediment cores studied.

The age-depth model for the 4016 sediment core is based on 8 radiocarbon dates obtained on selected species of planktonic foraminifera (>125μm; G. ruber, G. sacculifer and G. minardi) using the NSF accelerator mass spectrometer (AMS) facility at University of Arizona, USA. AMS radiocarbon ages have been calibrated to calendar ages using Marine13 calibration curve in Calib 7.1.0 online tool (Reimer et al., 2013) with a reservoir age correction of 129±35 a (Dutta et al., 2001). The age-depth model for the 4018 sediment core has been adopted from the previously published dataset (Tiwari et al., 2010).

The geochemical and isotopic analyses were carried out using the research facility available at Geoscience Division of Physical Research Laboratory, Ahmedabad. For the analysis of organic matter, small aliquot of sediment samples were acidified using 10% HCl to remove the inorganic carbonate. Acid treated samples were then packed in tin foils and loaded in elemental analyser (Fisions) to measure the concentration of total organic carbon and nitrogen. High organic soil sample (HOSS) and Low organic soil sample (LOSS) were used for instrument calibration. The $CaCO_3$ concentrations were measured in bulk samples using the Coloumeter. Biogenic silica fraction was separated from the sediments using Colman and Carter method of alkaline extraction. The Biogenic silica concentration in the extracted solution is measured in the inductively coupled plasma atomic emission spectroscopy (ICP-AES: Jobin-Yuvon). For the geochemical analysis the sediment samples were converted in to liquid form using a particular ratio of HCl, HNO_3 and HF acids by microwave digestion procedure (Milestone microwave digestor). The digested samples were dried and diluted with 0.4N HNO_3. The major elemental composition (Al, Fe, Ca and Mg) in the diluted samples were measured using the ICP-AES. The trace elements and REE's were measured in Q-ICP-MS. Along with the samples an international sediment standard MAG (USGS) and lab standard NOVA was digested and measured to assess the analytical procedure. The stable isotopic composition of organic Nitrogen were measured in the bulk sediment samples using the Finigon MAT-IRMS facility with the guidance of Dr. Sanjeev Kumar, PRL. The stable isotopic composition of organic carbon were measured in the decarbonated fraction of the sample. The isotopic composition of Strontium and Neodymium in the silicate fraction of selected samples from both the sediment cores were analysed following the procedure of Singh et al., 2008. The Sr and Nd concentrations and their isotopic ratios were measured using a Finnigan Neptune MC–ICP-MS.

Results and discussion

The results obtained from the analyses of biogenic silica flux, major elements, Sr- Nd isotopes, Organic Nitrogen isotope along with the chronological data have been synthesized to achieve the proposed objectives of the study as under:

Evolution of relationship between Somali upwelling and southwest monsoon rainfall in the last 18.5 ka

The high surface production of biogenic silica during SWM upwelling (Haake et al., 1993; Koning et al., 1997), together with the increased burial efficiency of upwelling-indicating diatoms (biogenic silica) in the western Arabian Sea sediments (Koning et al., 2001), makes biogenic silica flux as a potential proxy for SWM-related upwelling in the 4018 sediment core location. The biogenic silica concentrations (3–5 %) and fluxes (~2 g.m-2.y-1) were lowest during the 18.5-15 ka BP, which is similar to earlier findings of low productivity during glacial periods from the western Arabian Sea (Burckle, 1989; Sirocko et al., 2000; Ivanochko et al., 2005). Based on the modern pattern of biogenic silica productivity and its burial efficiency in the western Arabian Sea, the observed low fluxes of biogenic silica indicate that the Somali upwelling was very weak during the 18.5-15 ka BP. Weakened SWM rainfall during the 18.5-15 ka BP has also been envisaged by Anand et al. (2008) based on high $\delta^{18}O$ in sediment core off Goa, while Govil and Naidu (2010) observed evidence of high salinities in a sediment record from off Goa that was attributed to high evaporation and low fresh water influx. Based on the weak upwelling in the western Arabian Sea and the increase in evaporation and reduced fresh water influx to the eastern Arabian Sea, it is concluded that the SWM was weak during 18.5-15 ka BP. The beginning of the B/A (15-13 ka BP) is marked by an abrupt increase in biogenic silica flux, which we attribute to the effect of entrainment of the SWM at our core site and the subsequent increase in Somali upwelling strength. The $\delta^{18}O_w$ record from core SK-17 (Anand et al., 2008) shows depleted values, indicating higher influx of fresh water from the Western Ghats caused by high SWM rainfall, during the B/A. The AAS9/21 record (Govil and Naidu, 2010) shows decreased sea surface salinity during the B/A caused by increased fresh water flux into the eastern Arabian Sea that was derived from SWM rainfall. The positive correlation between Somali upwelling (high biogenic silica fluxes and lower SSTs) and SWM rainfall in the Western

Ghats (high fresh water influx to the eastern Arabian Sea) during the B/A contrasts with the present-day scenario as observed by Vecchi and Harrison (2004). Thus, it is proposed that the moisture source for SWM rainfall during the B/A period was different from the modern source. The other possibility, that rainfall in south-western India was enhanced due to a strong NE monsoon during the B/A, is unlikely because the siliceous productivity in the western Arabian Sea related to the NE monsoon has not been reported (Koning et al., 1997; Ramaswamy and Gaye, 2006). In contrast to the B/A, the upwelling in the western Arabian Sea was weak during 13-11 ka BP, as revealed by the low biogenic silica fluxes and high SSTs (Huguet et al., 2006). Furthermore, the high $\delta^{18}O_w$ and high surface salinity values in the eastern Arabian Sea (Anand et al., 2008; Govil and Naidu, 2010), which were caused by low freshwater influx, also points to weak SWM rainfall. The onset of the Holocene (11 ka BP) is marked by an abrupt increase in biogenic silica flux. This sudden increase in biogenic silica fluxes between 11 ka and 9 ka BP might have been caused by the intensification of the SWM (extended season) due to a northward shift of the ITCZ following the peak in Northern Hemisphere solar insolation (Fleitmann et al., 2007). The $\delta^{18}O_w$ and salinity records (Anand et al., 2008; Govil and Naidu, 2010) indicates reduced rainfall (lower fresh water influx) over the Western Ghats. This negative correlation between Somali upwelling and SWM rainfall over south-western India during the early Holocene (11 ka to 9 ka BP), marks the establishment of the modern-day climate system. Upwelling strength decreased after 9 ka BP in the western Arabian Sea compared to the early Holocene, indicating the presence of the SWM with reduced wind strengths relative to the early Holocene. The eastern Arabian Sea records show an increase in fresh water influx from the Western Ghats at this time (Anand et al., 2008; Govil and Naidu, 2010). During the last 8 ka, along with the gradually increasing upwelling trend, there are two events showing enhanced upwelling centered on 5 and 2 ka BP, marked by slight increases in biogenic silica fluxes in our record from core 4018 and decreases in Somali basin SSTs (Huguet et al., 2006; Saher et al., 2007; Anand et al., 2008). The low biogenic silica fluxes observed in our core during the same time period (5 to 3 ka BP) indicate lower upwelling but more rainfall during the SWM. The speleothem record from Oman (Fleitmann et al., 2007) also exhibits anti-correlation with the Somali upwelling record, indicating the influence of Somali upwelling on rainfall over the Arabian Peninsula during the SWM. Overall, it has been noted that the Somali upwelling had a negative impact on southwest monsoon rainfall over south-western India throughout the Holocene.

Aeolian flux in the western Arabian Sea during the last 19 ka and its influence on carbon export flux

The weight percent of aeolian content in sediment samples of 4018 core is determined by isolating the terrigenous fraction of the sediment by eliminating carbonate, opal and organic matter (Rea, 1994; Kohfeld and Harrison, 2001). Identifying aeolian fraction with this method in coastal marine sediments is difficult, as its terrigenous fraction is mainly composed of fluvial sediments. But these fluvial sediments are confined to humid tropical coasts. Terrigenous component of sediments present in Open Ocean and coastal areas surrounded by deserts (like the 4018 core location) are mostly devoid of fluvial sediments. Thus, the aeolian fraction in marine sediment collected from such areas can be directly calculated by subtracting the biogenic component from total. Aeolian flux is the product of aeolian fraction, sedimentation rate and dry bulk density. Aeolian fraction ranges from 15 to 35 % during last 19 ka BP in the study area. Highest concentration (~35 %) is observed at 19 ka BP and then it decreased to 30 % at 18 ka BP. After 18 ka BP, Aeolian fraction increased and peaked at 15.5 ka BP. There is an abrupt negative shift in aeolian fraction (35 to 22 %) observed after 15.5 ka BP within about 0.5 ka. Subsequently, it gradually decreased to its lowest value at 9.5 ka BP except during 12 to 11 ka BP showing positive shift. After 9.5 ka BP, the aeolian fraction continuously increased until 3 ka BP with minor variations. During the last 3 ka BP, there was a minima observed at 2.5 ka BP and a maxima at 1 ka BP. Aeolian flux varied between 8 to 16 g.m-2.y-1 with lowest value being observed at 9.5 ka BP and maximum at 15.5 ka BP. The carbon export flux estimated from the flux of excess barium in the sediment samples using the equation given in Francois et al., (1995). Export flux in north western Arabian Sea shows ~10 fold variation in last 19 ka. Lower values observed at the bottom of the sediment core. It was 4 gC/m2/y at 19 Ka BP, then increased around three times gradually and reached 12 gC/m2/y at 17 ka BP. After 17 ka BP it gradually decreased in next 1.5 ka and attained its minimum of 2 gC/m2/y at 15.5 ka BP. After attained its minimum value, export flux again gradually increased from 2 to 19 gC/m2/y until 13 ka BP with a low value (12 gC/m2/y) centred at 12 ka BP. There is an abrupt negative shift in export flux observed at 13 ka BP as same as BaeC. Again there is a decrease observed between 13 to 12 ka BP from 6 to 4 gC/m2/y. After 12 ka BP export flux sharply increases to 32 gC/m2/y in 2 ka and then it decreases to 19 gC/m2/y in another 2 ka with two lows between 9 to 10 ka BP. From 8 ka BP onwards export flux raises until 6 ka BP (42 gC/m2/y) and then it falls down to 27 gC/m2/y at 3.7 ka BP. In the next 1.5 ka export flux shows positive shift from 27 to 40 gC/m2/y. After 2.2

ka BP export flux slightly decreased and reached the modern value of 35 gC/m2/y. Overall export flux shows an increasing trend in the last 19 ka in our study area. The maxima in aeolian flux has been observed between 19 and 15 ka BP. However the carbon export flux was low during the same time period indicates low surface productivity. Export flux was increased during Bolling-Allord period (15-13 ka BP) but the dust flux shows a decreasing trend during this period. During the Younger dryas (13-11 ka BP) the dust flux increased and the carbon export flux decreased. Short term fluctuations in the carbon export flux has been observed during Early Holocene period (11-9 ka BP). However the dust flux show and steady decrease during 11-9 ka BP. Moreover the Dust and carbon export flux has been observed to be negatively correlated during the period between 19 to 9 ka BP, which indicates that dust fall during this period inhibited the surface productivity either by limiting sunlight penetration or low nutrient content. Since 9 ka BP the dust as well as the carbon export flux has been increased. This co-relation between dust and export flux during the last 9 ka is attributed to the intensified southwest monsoon and co-occurrence of upwelling and dust fall. The upwelling brings macronutrients (Nitrate, Phosphate) and the dust brings micro-nutrients like Fe, both have caused the increase in the surface productivity. However there were short term variations in both the records with anti-correlation has been noticed. The provenance analysis of terrigenous fraction using the Strontium-Neodymium systematics would be helpful to understand the reasons for the short term variations.

Productivity in northern Arabian sea during the last 35 ka: Implications to monsoon and hydrography

Organic productivity proxies (OC and N) demonstrate noticeable variations during the last 35 ka. Organic matter flux influenced either by changes in surface productivity or preservation. However Reichart et al., 1998 shown that the organic carbon flux in the northern Arabian Sea is primarily controlled by surface productivity. The location of the present sediment core 4016 is being located in the Indus submarine fan could arise question on the source of organic matter preserved in the sediments. The C/N ratio of the 4016 sediment core samples fall well within the range of marine organic matter and this denies the possibility of source induced (Indus river derived) changes in flux and isotopic composition of organic matter observed in the present record. However there is a prominent negative shift in the C/N ratio from 9 to 6 has been noticed at around 16 ka BP. This shift in C/N ratio might have been caused by the changes in the nutrient availability (more nitrate) and increased incorporation of nitrogen by marine phytoplankton. High C/N values were observed in the modern marine organic matter from the oceanic regions with high inorganic carbon and low nitrate pools. The observed variations in the organic carbon and nitrogen in 4016 sediment record show four different sets of value at separate time periods marking variation in surface productivity. The surface productivity was relatively high during the period between 35 to 23 ka BP, about 60% of the productivity observed at LGM (23-16 ka BP). Surface productivity was at its maximum in the study area during LGM period indicated by the high concentration of organic carbon and nitrogen. In the modern scenario, the annual productivity maxima in the study area is observed during the southwest monsoon period and the second highest productivity is noticed during the northeast monsoon period. However previous studies shown that the southwest monsoon was very weak or absent during the LGM period caused by the southward shift of ITCZ (Sirocko et al., 2000; Ivanochko et al., 2005). There could be two reasons for the observed high productivity during LGM, 1) nutrient flux to the euphotic zone through convective mixing, 2) Increase in atmospheric deposition of bioavailable nutrients. Dahl and Oppo (2006) noticed that the SST in the Arabian Sea was 2-4^0 C lower during LGM period. Surface cooling during LGM might have caused nutrient enrichment in the euphotic zone through convective mixing and thickened mixed layer. The atmospheric deposition of nutrients also have influenced the productivity due to the fact that the LGM period was arid and dusty. Sirocko et al., (2000) noticed high dust flux originated from Arabia and Persian Gulf regions to the Arabian Sea during LGM. Hence the high productivity during LGM was caused by both the factors, the nutrient enrichment by convective mixing and high atmospheric. Importance of the high productivity noticed in the Arabian Sea during LGM period for the drawdown of atmospheric CO2 yet to be explored. The LGM period is followed by a 6 ka long phase (16-10 ka BP) of comparatively low concentrations of organic carbon and nitrogen. This period marks the surface productivity minima in the Arabian Sea in the studied time span of the last 35 ka with a minor positive high between 15-13 ka BP. This 2 ka period is synchronous with the well-known climatic phase namely Bolling-Allord (B/A) event. The deglacial intensification of southwest monsoon at ~15 ka BP has seem to be the reason for the observed productivity during B/A. Since 10 ka BP the surface productivity in the Northern Arabian Sea have been increased. Intensified southwest monsoon is attributed for the high productivity occurred during Holocene (since 10 ka BP).

Sedimentation in the northeastern Arabian sea during the last 35 ka: Implications to climate and tectonics

High MAR of ~40g/m2/a is observed during the last glacial maximum in 4016 sediment core. There is a near symmetrical decrease in MAR during pre and post-LGM periods. Lowest MAR values were observed throughout Holocene period (last 10 ka). Globally LGM period is marked by reduced precipitation and enhanced aridity. If that is the case then the LGM period should have low MAR in the studied time span. One of the possibility is the redistribution of shelf sediments by wind and rejuvenated river during LGM low sea stand. Because the eustatic sea level was ~120 m lower than present day during the LGM (ref). Redistribution of older sediments should cause reversal in age-depth model, this is not the case in 4016 sediment core. Also the study area is located in open Ocean far off from the shelf region (water depth 3242 m). So the influence of sediment redistribution can be rejected for the observed MAR variations at LGM. Second possibility is the increased detrital supply by Indus River to the core location. To deliver high detrital supply the discharge volume of the river water need to be high indirectly the rainfall should be high. As per current understanding the southwest monsoon was weak during LGM and the fact that modern Indus discharge is high during summer, indicates negligible influence of riverine discharge on the observed MAR at LGM. Increased winter precipitation during LGM can influence MAR by increasing riverine sediment discharge. Testing above mentioned scenario is difficult with the present data set. Aeolian influx can be an alternate mechanism for the high MAR which is supported by the dry and arid climate at LGM. High concentration of carbonate free Magnesium (proxy for Arabian dust; Sirocko et al., 2000) observed during LGM indicate that the Atmospheric deposition is best possible model for the observed high MAR at LGM. The observed low MAR values during Holocene period mismatch with the paleoclimate records which shows intensified monsoon precipitation at early Holocene. The carbonate free Magnesium concentration declined during deglacial period and remained low throughout Holocene. So the reduction in Aeolian flux is one of the reason for the reduced MAR at Holocene. Increase in the sediment accommodation space in coastal and continental shelf region due to sea level rise during post glacial period also seems to be a causative factor for low MAR during Holocene.

Summary

- The present study throws more light on the fluctuating southwest monsoon intensity during the Holocene .It appears that previous studies did not consider the internal feedback mechanism that caused the anti-correlation between marine and terrestrial records.
- The intensification of southwest monsoon caused increase in Somali upwelling that reduced the surface area of moisture source in the western Indian Ocean and subsequently reduced the rainfall over Indian sub-continent during the Holocene.
- The aeolian flux and export flux in the western Arabian Sea record show negative correlation during 19 to 9 ka BP suggesting that the aeolian flux has inhibited the surface productivity through low nutrient content or light limitation. Since 9 ka BP the aeolian and export flux show positive correlation which might have been caused by the co-occurrence of southwest monsoon upwelling and nutrient rich aeolian flux.
- Productivity in the northern Arabian Sea shows noticeable variations during the last 35 ka. The proxy records show four periods of productivity changes in the studied time span, which are 35-23 ka BP, LGM (23-16 ka BP), 16-10 ka BP and Holocene (10-1.3 ka BP).
- The maxima in surface productivity has been observed during the LGM and attributed to the increase in convective mixing and dust supply. Relatively high productivity observed during the Holocene has been caused by the increase in surface nutrients through advection of upwelled water from Omani coastal region.
- The northern Arabian Sea sedimentation record during the last 35 ka shows a Gaussian type curve with the maximum sedimentation at LGM period. Reduced sea level and increased aeolian activity were the causative factors for the observed high sedimentation during LGM. Hence it is surmised that the sedimentation in Northern Arabian Sea was primarily controlled by the climate rather than tectonics.

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