PALAEOCLIMATIC RECONSTRUCTIONS BASED ON MARINE SEDIMENTS FROM THE NORTHERN INDIAN OCEAN: IMPLICATIONS TO AEOLIAN FLUX AND PRODUCTIVITY

Executive summary

of the thesis submitted

By

BALAJI D

Department of Geology

Faculty of Science

The Maharaja Sayajirao University of Baroda

Vadodara-390002, Gujarat

2022

Introduction

India's economy is largely dependent on rainfall from the southwest monsoon (SWM); hence, slight changes in SWM rainfall can have immense societal impacts in this region. Numerous endeavours have been made to understand the factors responsible for SWM rainfall variations, and several global phenomena have been correlated with variations in SWM rainfall. It has been identified that the Indian Ocean warm pool (IOWP) is the prominent source of moisture for SWM rainfall. However the present understanding on global and regional processes which governs the dynamics of SWM rainfall needs further exploration/study. Therefore, one of the objectives of the present study was aimed to understand past variations in Somali upwelling strength and its impact on SWM rainfall. Apart from SWM rainfall, carbon export flux (CEF) is intimately related with the global climate through the modulation of CO_2 in the atmosphere and its influence on the heat budget are also important. Increase in CEF has been suggested as a reason for the reduction in atmospheric CO_2 during Last Glacial Maximum (LGM). Aeolian flux was assumed as the nutrient supplier for the increased CEF during LGM. Though the relation between CEF and aeolian flux were much studied in high nutrient and low chlorophyll (HNLC) regions, their relation in other oceanic regions need attention.

The Arabian Sea forms a natural laboratory to study the marine biogeochemistry. Number of studies have been carried out from various regions of the Arabian Sea, especially from the coastal regions of northern part for understanding the palaeoclimate, productivity and denitrification processes. However the impact of other physical processes like lateral advection of nutrients on productivity and nitrogen cycling in open ocean region needs to be understood. Numerous studies in the recent times have been aimed at to understand the evolution of Indus submarine fan sedimentation. Previous studies have shown that a significant portion of the eroded sediment in the Indus drainage system is stored in the floodplains except the suspended loads. Another study has shown that the sediment transfer from river mouth to submarine fan is mainly controlled by sediment mixing and reworking associated with sea-level changes. Therefore the correlation of sedimentation in the Indus submarine fan and climate over the Indus drainage basin is very complex. Thus, comparison of sediment flux reconstructions with climate, tectonic changes in source area and sea level changes may help in understanding submarine sedimentation.

Methodology

Two sediment cores, one from western Arabian Sea (4018) and one from northern Arabian Sea (4016) are selected to accomplish the objectives of the present study. The sediment core (4018) from western Arabian Sea was selected to reconstruct the palaeo-upwelling and its impact on SWM rainfall, aeolian flux and its influence on CEF. The location of 4018 sediment core is 13° 12.8' N latitude and 53° 15.4' E longitude. Core length is 130 cm and the water depth at core location is 2830 m. The core is located in the Somali upwelling region where intense upwelling takes place during SWM season. Total organic carbon, Total nitrogen, Biogenic silica, Major and trace elements and Magnetic susceptibility analysis of 4018 sediment core has been carried out.

The other core (4016) is located on the middle Indus submarine fan in Northern Arabian Sea (19.765^{0} N, 64.61^{0} E) at a water depth of 3242 m. The 4016 sediment core is 147 cm long and subsampled onboard at 2 cm interval. The location of 4016 sediment core is best suited to study the open ocean conditions and Indus sediment flux during the past. Age model for 4016 is based on 8 nos. of AMS ^{14}C dates measured in NSF accelerator mass spectrometer (AMS) facility, University of Arizona, USA. Total organic carbon, Total nitrogen, Isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), Major and trace elements and Magnetic susceptibility analysis of 4016 sediment core has been carried out.

Somali upwelling and Southwest monsoon rainfall during the last 18.5 ka

The somali upwelling strength during the last 18.5 ka B.P. has been reconstructed using biogenic accumulation rate and compared with palaeo-rainfall record from the eastern Arabian Sea and a speleothem record from Oman. The biogenic silica flux record does not show any distinct variation between the previously identified Heinrich event 1 and the Last Glacial Maximum (LGM), so the period between 18.5 and 15 ka is considered here as the Last Glacial Period (LGP). Biogenic silica fluxe (~2 $g.m^{-2}.y^{-1}$) was lowest during the LGP, which is similar to earlier findings of low productivity during glacial periods from the western Arabian Sea. 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 LGP. Palaeo-rainfall record from eastern Arabian Sea shows high $\delta^{18}O_w$ IVF values indicative of reduced freshwater flux and rainfall during this period. Based on the weak upwelling in the western Arabian Sea and the reduced fresh water influx to the eastern Arabian Sea, it is concluded that the SWM was weak/absent during the LGP.

The Deglacial Period (DP) is a connecting phase between two entirely different climatic periods, the LGP and the Holocene. The DP is actually a composite of two millennial scale events between 15–12.9 ka and 12.9–11.7 ka B.P. The period occupied by these two events nearly coincides with well-known climatic events, specifically the Bølling-Allerød (B/A) event and the Younger Dryas (YD) event. The beginning of the B/A is marked by an abrupt increase in biogenic silica flux attributed to the effect of northern limit of southwest monsoon that was attained at the study site and the subsequent increase in Somali upwelling strength. The $\delta^{18}O_w$ IVF record from core SK-17 shows depleted values, indicating higher influx of fresh water from the Western Ghats caused by high SWM rainfall, during the B/A. The positive correlation between Somali upwelling (high biogenic silica flux) and SWM rainfall in the Western Ghats (high fresh water influx to the eastern Arabian Sea) during the B/A contrasts with the modern observations. Therefore, it is proposed that the moisture source for SWM rainfall over Western Ghats during the B/A event was different from the modern source. In contrast to the B/A, the upwelling in the western Arabian Sea was weak during the YD, as revealed by the low biogenic silica flux. Furthermore, the high $\delta^{18}O_w$ IVF in the eastern Arabian Sea, caused by low freshwater influx, also points to weak SWM rainfall.

The beginning of the Holocene is marked by an abrupt increase in biogenic silica flux. This sudden increase in biogenic silica fluxes between 11.7 ka and 9 ka B.P. can be attributed to the intensification of the SWM (extended season) caused by the northward shift of the ITCZ following the peak in Northern Hemisphere solar insolation. The synchronous changes in the biogenic silica flux with biogenic silica/carbonate ratio indicates a change in dominant plankton community (carbonaceous to siliceous) due to increased upwelling. The $\delta^{18}O_w$ IVF display values similar to those of the YD during the early Holocene, indicating reduced rainfall (lower fresh water influx) over the Western Ghats. This anti-correlation between Somali upwelling and SWM rainfall over south-western India during the early Holocene (11.7 ka to 9 ka B.P.), marks the establishment of the modern-day climate system. The increased Somali upwelling in the western Arabian Sea during the early Holocene (11.7 to 8 ka B.P.) might have reduced the IOWP expanse during the SWM season, thereby resulting in lower moisture availability and subsequent reduced rainfall over the Western Ghats. At ~8 ka B.P. Somali upwelling strength is seen to have decreased as compared to the early Holocene but persisted above YD and B/A levels, indicating the presence of the SWM with reduced wind strengths relative to the early Holocene. This reduction in upwelling at 8 ka B.P. might have allowed the westward extension of the IOWP during the SWM season that increased both, moisture availability over the Arabian Sea and rainfall over the Western Ghats. The $\delta^{18}O_w$ IVF value is low at 8 ka B.P., pointing towards an increase in fresh water influx from the Western Ghats at this time due to increased SWM rainfall.

Somali upwelling had a gradual increase during the last 8 ka with minor positive changes at around 5 and 2 ka B.P. The eastern Arabian Sea sediment record shows slight increase in the $\delta^{18}O_w$ IVF of surface waters during the last 8 ka indicating reduction in SWM rainfall. The opposite trend in upwelling and rainfall record during the last 8 ka indicate the negative impact of Somali upwelling on SWM rainfall and might have been caused through a change in the area of IOWP and moisture availability. However the short term variations in upwelling are not observed in eastern Arabian Sea rainfall record. The Somali upwelling possibly had a negative impact on southwest monsoon rainfall over south-western India and Oman throughout the Holocene.

Carbon export flux and Aeolian flux in the western Arabian Sea

Aeolian flux has been identified as an important source for nutrients to the oceanic surface productivity especially for the remote oceanic regions with abundant macro-nutrients. Becasue the aeolian flux act as a supplier of micronetrients like Fe which is important for the phytoplankton growth. Though the present study area is not considered as an high nutrient region like southern ocean, but recent studies have revealed that the western Arabian Sea mimics High Nutrient Low Chlorophyl (HNLC) conditions during the peak monsoon season. The aeolian flux and carbon export flux are compared in the present study to give a preliminary assesment on the long term relation between them. Aeolian flux versus CEF for the duration from 18.5 to 11.7 ka B.P. shows a negative correlation, which suggests that the increase in aeolian flux leads to decrease in the surface productivity. This is in contradiction to the conventional idea that the increase in aeolian flux would increase the micro-nutrient (Iron, Zinc, etc) availability that leads to higher productivity. However the positive correlation between aeolian flux and productivity is valid in the presence of macronutrients (like Nitrogen, Phosphorous, etc). If there is not enough macronutrients then the aeolian flux may not have any influence on the productivity but it can reduce sun light penetration through turbidity. Thus it is inferred that the availability of macro-nutrients were limited in the western Arabian Sea during 18.5 to 11.7 ka B.P. Though the productivity reconstruction suggests the southwest monsoon induced upwelling was high during

15 to 12.9 ka B.P., the CEF to aeolian flux relation remained negative which indicates that the upwelling was not enough to keep the surface waters with macro-nutrients in excess.

The aeolian flux and CEF shows positive correlation during the last 11.7 ka B.P. Based on productivity, it is inferred that the southwest monsoon induced upwelling was high throughout Holocene and caused high productivity. The increased upwelling might have created HNLC like conditions in the study area during Holocene. The increased aeolian flux could have supplied more micro-nutrients and lead to increased CEF throughout Holocene. Therefore the present study infers that the HNLC like condition during southwest monsoon in Arabian Sea set in at the beginning of Holocene. It is also indicated that the northern Arabian Sea in general and north-western in particular are not the parts of the last glacial biological pump that reduced atmospheric CO_2 to LGM levels.

Productivity and nitrogen biogeochemistry in the Northern Arabian Sea during the last 34.6 ka

In the modern scenario the surface productivity in the Northern Arabian Sea during southwest monsoon is fuelled by the nutrient supply from Oman coastal upwelling region through lateral advection. The advection of upwelled water influences the upper–ocean heat budget in Arabian Sea and is also important in the meridional transport of heat. Comparison of present $\delta^{15}N$ record with Oman margin record can throw some light on past changes in the lateral advection of nutrients to the northern Arabian Sea. If the variation in $\delta^{15}N$ was caused by pelagic denitrification alone then the depth corrected $\delta^{15}N$ of coastal and open ocean records should be similar within the error limits. The $\delta^{15}N$ fluctuations in coastal and open ocean records are synchronous and indicate the basin wide presence of causative process. The short term variations were not comparable as the data points were not similar in the $\delta^{15}N$ records. Overall, the open ocean $\delta^{15}N$ values were little higher than the coastal records. Both the records show similar $\delta^{15}N$ values (difference is $\leq 1‰$) between 34.6 to 15 ka B.P. with minor variations at 31, 29, 27-23 and 21 ka B.P. The difference in $\delta^{15}N$ records during 31, 29, 27 to 23 and 21 ka B.P. may be caused by short spells of advection of coastal waters with partially utilized nutrients. However it requires further studies to understand the causative process. Since 15 ka B.P., the $\delta^{15}N$ values of the open ocean record are clearly distinguishable from coastal records which have been >1‰ higher. The primary cause for the increase in organic $\delta^{15}N$ was the de-glacial intensification of pelagic denitrification and southwest monsoon, subsequent supply of nutrient from subsurface i.e. OMZ. However the $\delta^{15}N$ difference between coastal and open ocean indicates the presence of secondary process. The lateral advection of upwelled waters seems to be the secondary process which increases the open ocean $\delta^{15}N$ value. Upwelling in the Oman coastal region is too intense and causes partial nutrient utilization prior to upwelled waters (nutrients) being laterally advected away resulting into an increase in the $\delta^{15}N$ value of remaining nitrate.

However this gradient in $\delta^{15}N$ can vary with the intensity of lateral advection; high advection causes low gradient and vice versa because low advection allows more nutrient consumption during its path from the upwelling zone to the core location and leaves nitrate being highly enriched in ^{15}N. The increase in the intensity of lateral advection was the cause for similar $\delta^{15}N$ values in coastal and open ocean records at 15-14 and 11-10 ka B.P. The gradient in $\delta^{15}N$ steadily increased during the Holocene from 1‰ at 10 ka B.P. to 2‰ in late Holocene. A decline in the intensity of lateral advection during the southwest monsoon season caused the observed increase in $\delta^{15}N$ gradient. However the remaining nutrients were substantial to help the productivity. Based on evidence for the presence of lateral advection of upwelled water, it can be further surmised that the southward meridional transport of heat in the northern Arabian Sea has continued since 15 ka B.P.

Sedimentation in the northeastern Arabian sea during the last 34.6 ka: Implications to climate, tectonics and sea level

Lithogenic sedimentation in the Indus submarine fan has been reconstructed using the present sediment core data along with previously published data sets. The lithogenic sedimentation was higher during the period 34 to 29 ka B.P. The sediment distribution was asymmetric with southern part having higher sediment flux than northern part of the river mouth. This suggests that there was an influence of clockwise surface currents in the study area during 34 to 29 ka B.P. leading to enhanced sedimentation in the southern part. The secondary sedimentation maxima at 20° N also indicates the persistent influence of dust flux in the distal fan sedimentation. The average lithogenic sediment flux during 29 to 26 ka B.P. was comparatively lower than during the period 34 to 29 ka B.P. The asymmetric distribution of sedimentation towards southern side of the river mouth suggests clockwise surface circulation. The surface circulation indicates the presence of southwest monsoonal winds, but with reduced sediment flux from Indus River. The secondary sedimentation maxima which also occurred during this period indicates the influence of dust flux. The maximum sedimentation occurred on the northern part of the river mouth. This indicates alteration in sediment redistribution thereby the change in surface current direction. In the modern scenario, the surface current flows counter-clockwise during the northeast monsoon season and redistributes the Indus derived sediments towards north. The sedimentation pattern during the period 26 to 17 ka B.P. matches with the northeast monsoon surface circulation pattern. Thus, northward distribution of sediment during this period could be due to strengthening of the northeast monsoon.

During the 17 to 11.7 ka B. P. the sedimentation was much higher. Not only the lithogenic sediment flux increased, but also the asymmetric nature of sediment deposition on either side of river mouth. This indicates stronger clockwise surface currents during this time thereby stronger southwest monsoon. The present dataset however indicates strengthened southwest monsoonal surface currents during deglacial period (17 to 11.7 ka B.P.). The high sedimentation during 17 to 11.7 to ka B.P. occurs near the coast as well as in the deep submarine fan indicating the massive sediment load debouched by the Indus River. The average lithogenic sediment flux for the last 11.7 ka B.P. is the highest near the river mouth. However, the maximum flux occurs at the southern part of the river mouth, making an asymmetric distribution of sediment. The clockwise surface currents might have redistributed the sediment load towards the southern part making maximum sedimentation in southern part of the river mouth. Overall, it has been interpreted from the sedimentation pattern in the Indus submarine fan that the Indus derived sediments undergo reworking by surface water currents and get mixed with other sediments. Most of the sediments derived from the Indus River during the last 34 ka B.P. was distributed southwards due to clockwise currents, except during LGM when the sediments were transported towards north by counter-clockwise surface currents. The overall pattern shows the maximum lithogenic flux occurred during the deglacial period.

Lithogenic sediment flux has been compared with the global sea level fluctuations to understand how the sea level influenced the sedimentation during the last 34.6 ka B.P. The lithogenic sediment flux in the present core record (4016) shows an inverse relation with the sea level, high sediment flux during low sea level and vice versa. The inverse relation clearly indicates that the sedimentation in the 4016 core region is significantly influenced by the variation in mean sea level. The sea level during the time period between 34.6 to 29 ka B.P. was nearly stable, lower than present and higher than LGM. The sediment flux was also moderate during this period. From 29 ka B.P., the sea level regressed, while in the meantime the lithogenic sediment flux increased. The decreasing sea level reduced the storage capacity for sediment deposition in the shelf region and increased the sediment supply towards deeper parts of the submarine fan. This process was again accelerated during the LGM period (26 to 17 ka B.P.) by the lowest sea level.

Highest lithogenic sediment flux was observed during the LGM in the 4016 sediment record. After the LGM, the sea level again increased during 17 to 11.7 ka B.P., while the lithogenic sediment flux decreased by the production of more storage capacity in the shelf region. However the average lithogenic sediment flux in the basin increased during 17 to 11.7 ka B.P. The increasing pattern in the average sediment flux were mainly caused by the near coastal records. During the last 11.7 ka B.P., the sea level increased again and reached present day sea level, while the lithogenic sediment flux decreased to its lowest rate. The 4016 record as well as the previously published record show similar reduction in lithogenic sediment flux during the last 11.7 ka B.P. Overall, it has been observed that the variation in sea level had significant control on the lithogenic sediment flux to the Indus submarine fan throughout the last 34.6 ka B.P. The comparison of Himalayan climate with Indus submarine fan sedimentation shows an interesting relation. The high sediment flux was recorded during cold and weak monsoon period (29-26 and 26-17 ka B.P.), but low sediment flux is observed during warm and strengthened monsoon period (last 11.7 and 34.6 to 29 ka B.P.). This negative relation between the Himalayan climate and Indus fan sedimentation is not expected. However, there are other possible reasons that could have caused the negative relation. It can be caused by the mask effect of sea level influence on sedimentation, means that the climate may have had a positive relation, but the stronger influence of sea level masked it. Other possible reason for the high sediment flux during weak monsoon phase might be the ice cover. The western Himalayan region experienced no major advance in ice cover during LGM, instead more ice cover could be observed during warm monsoonal phase like early Holocene. The less ice cover could have exposed the glacier eroded sediments and the melting might have caused more sediment discharge during LGM. The extended ice cover during warm monsoonal phase might have caused the opposite. However, the relation is more complex and could not be explained with the present dataset.

The relation between the Himalayan tectonics and Indus submarine fan sedimentation shows that the high incision rates are correlatable with low sedimentation and vice versa. Highest incision rates were recorded around 14 and 6 ka B.P., while the lowest incision rates were observed during LGM and during modern period. However, the highest lithogenic sediment flux to the Indus submarine fan was recorded during the LGM. Aggradation in the fluvial plains might be the possible reason for the low sedimentation during the high incision periods. But the erosion of fluvial plain deposits caused by lowered sea level can be a reason for the high sediment flux during LGM. Therefore, a detailed study on the fluvial plain deposition would be necessary before making any conclusive statement on the relation between the western Himalayan tectonics and the Indus submarine fan sedimentation.

Summary

The thesis deals with reconstruction of the variability of Somali upwelling, aeolian influx, carbon export flux, nitrogen biogeochemistry and Indus fan sedimentation during the last 18.5 ka and 34.6 ka B.P. from two marine sediment cores (4018 and 4016) collected from the Western and North-eastern Arabian Sea. Such studies are essential to understand the internal feed-back mechanism of SWM. An attempt is therefore made to improve the current understanding regarding the influence of Somali upwelling on SWM precipitation, aeolian flux, carbon export flux, lateral advection of upwelled water on nitrogen biogeochemistry and sea level, climate and tectonic changes.

Somali upwelling intensity during the last 18.5 ka B.P. has been reconstructed using biogenic silica concentration in marine sediment cores from the western Arabian Sea (4018). The Somali upwelling was weak/absent due to the absence of southwest monsoonal winds during Last Glacial Period (LGP). While the precipitation in the south-western India was restricted due to the absence of southwest monsoonal winds and Indian Ocean Warm Pool (IOWP). These processes collectively address the positive relation between Somali upwelling and SWM precipitation during LGP. The post-glacial onset of the southwest monsoon was marked by an increase in the strength of the Somali upwelling at 15 ka B.P., with the eastern Arabian Sea records showing increased southwest monsoon rainfall. The observed positive relation between Somali upwelling and SWM precipitation during 15 to 12.9 ka B.P. is attributed to change in the moisture source area. It has been proposed that the moisture source area for the SWM precipitation during 15-12.9 ka B.P. was

restricted to central Indian Ocean, while the changes in the Somali upwelling might have had feeble influence on SWM precipitation.The Somali upwelling was weak between 12.9 and 11.7 ka B.P., indicating another phase of weak southwest monsoon similar to that of the LGP. Weak SWM was probably caused by the southward shift of the ITCZ during 12.9 to 11.7 ka B.P. Overall, records of the Somali upwelling and southwest monsoon rainfall exhibit positive correlation between 18.5 and 11.7 ka B.P. Shift from the positive to negative relation between the strength of the Somali upwelling and southwest monsoon rainfall occurred at 11.7 ka B.P. at the beginning of the Holocene, which marks the establishment of modern day climate system. It is observed that the change in moisture source for SWM precipitation can alter the relation between the western Arabian sea upwelling and SWM precipitation. This will require further studies on the causative factors that can change moisture source region.

The Aeolian flux and Carbon Export Flux (CEF) during the last 18.5 ka B.P. has been reconstructed using terrigenous fraction and biogenic barium concentration in marine sediment core from the western Arabian Sea. Aeolian flux versus CEF shows negative relation for the time gap between 18.5 to 11.7 ka B.P., which suggests that the increase in aeolian flux had suppressed surface productivity. It is inferred that the availability of macro-nutrients was limited in the western Arabian Sea during 18.5 to 11.7 ka B.P. It is also inferred that the north-western Arabian Sea is not a part of the last glacial biological pump that reduced atmospheric CO_2 to LGM levels. Aeolian flux and CEF shows positive correlation during the last 11.7 ka B.P. Based on biogenic silica productivity it is inferred that the southwest monsoon induced upwelling increased throughout Holocene and caused high productivity. The increased upwelling might have created High Nutrient Low Chlorophyll (HNLC) like conditions in the study area during Holocene. The increased aeolian flux could have supplied more micro-nutrients and led to increased CEF throughout Holocene. The present study suggests that the modern observation of HNLC like condition during southwest monsoon in the Arabian Sea started at the beginning of Holocene.

The concentration and isotopic composition of nitrogen and organic carbon determined in the sediment core from the northern Arabian Sea (4016) provide a unique record of productivity and nitrogen biogeochemistry for the last 34.6 ka. Productivity maxima occurred during LGM and Holocene. The nitrogen isotopic composition demonstrates that denitrification was the primary controller of the nitrogen cycle in the northern Arabian Sea throughout the last 34.6 ka. Dominant role of convective mixing of water column is envisaged as a secondary process that influenced the nitrogen biogeochemistry during 34.6 to 16 ka B.P., whereas upwelling and lateral advection processes dominated during the last 16 ka. The increase in the $\delta^{15}N$ gradient observed between the coastal and open ocean records during the Holocene clearly indicates lower intensity of lateral advection of upwelled waters from Oman margin. Based on the evidence for the presence of lateral advection of upwelled water, it can be further surmised that the southward meridional transport of heat in the northern Arabian Sea has continued since 16 ka B.P. Further studies linking the influence of Arabian Sea productivity to the atmospheric carbon dioxide concentration during LGM and the effect of lateral advection on meridional heat transport may help us in understanding the regional climate.

The lithogenic sediment flux in the present study shows an inverse relation with the sea level, high sediment flux during low sea level and vice versa. The variation in sea level had significant control on the lithogenic sediment flux to the Indus submarine fan throughout the last 34.6 ka B.P. The comparison of Himalayan climate with Indus submarine fan sedimentation shows, high sediment flux during cold and weak monsoon period (29-26 and 26-17 ka B.P), but low sediment flux during warm and strengthened monsoon period (last-11.7 and 34.6 -29 ka B.P). Detailed study on fluvial deposition would be necessary to understand the Himalayan tectonics and Indus submarine fan sedimentation.