CHAPTER 7

A 70 kyr history of productivity in the Arabian Sea

Abstract

Millennial-scale variations in productivity associated with changes in the intensity of the Arabian Sea summer monsoon (ASSM) over the past 70 kyrs are assessed using two marine sediment cores, one from the Somali margin and one from the Indian margin. The productivity proxies (% Corg, Ba/Al) and the denitrification records indicate that on both sides of the Arabian Sea, the summer monsoon variability is evident with increased productivity and denitrification during Dansgaard-Oeschger interstadials and decreased values during Heinrich Events. On the Indian margin, glacial periods record continued elevated values of productivity and denitrification, despite the decrease in the ASSM intensity. This may relate to increased winter monsoon activity and deep convective mixing in the northeastern basin influencing the Indian margin site.
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**Introduction**

The intense, concentrated ASSM winds, which flow from the coast of Somalia over the Arabian Sea to India, develop in June and subside in late September (Figure 1A). These along shore winds generate an anti-cyclonic gyre in the northern Arabian Sea that facilitates Ekman transport off the coasts of Somalia and Oman. The consequent upwelling, which brings nutrient-rich deep waters to the surface, supports a summer productivity bloom that rivals the most productive areas of the ocean (Honjo et al., 1999). Strong surface currents and eddies create a heterogeneous environment (Brummer et al., 2002; Schott et al., 1990) that further enhances local biological productivity. In the coastal northwestern Arabian Sea near Oman, the flux of organic carbon reaches 80 mgC/m²/day and the total mass flux surpasses 750 mg/m²/day during the summer monsoon season (Honjo et al., 1999). This is compared to backgrounds of approximately 0 mgC/m²/day and 50 mg/m²/day respectively during the rest of the year (Honjo et al., 1999). Near Somalia, the large flux of organic matter through the water column and subsequent decay, consumes oxygen in the intermediate waters and an Oxygen Minimum Zone (OMZ) results where concentrations of O₂ are depleted to below 20 µM (0.48 ml/l) between 200-1200 m (de Wilde et al., 1997).

The summer monsoon anti-cyclonic gyre is also responsible for weak upwelling along the coast of southwestern India, which supports increased productivity during the summer season (Divakar Naidu et al., 1992). Chlorophyll maximums (up to 7.8 µg/l) are evident in the central and southeastern Arabian Sea during the summer monsoon and are accompanied by a deepening of the surface mixed layer from approximately 50 m to 100 m (Banse, 1987). Between July and September, sediment traps in the eastern Arabian Sea registered over a doubling of the total export flux to approximately 200 mg/m²/day (Nair et al., 1989) and *G. bulloides*, a foraminiferal species highly adapted to upwelling areas dominates the sediments of the southwestern Indian continental shelf (Divakar Naidu et al., 1992).

The northeasterly winter monsoon winds reverse the surface currents and suppress the coastal upwelling in the western Arabian Sea and the southern tip of India (Figure 1B). However the dry, cool, winter monsoon winds that originate in the Himalayas, both cool the surface waters and accentuates evaporation in the northeastern Arabian Sea, which concentrates the already saline waters and
convective mixing results (Madhupratap et al., 1996; Reichart et al., 2004; Reichart et al., 1998). The depth of the mixed layer in the Northeastern basin during the winter monsoon extends to 100 m during the winter monsoon, which replenishes the nutrient concentrations of the surface waters and supports a second productivity bloom of lesser importance to the summer bloom (Banse, 1987; Madhupratap et al., 1996; Schulte et al., 1999). The OMZ in the northeastern Arabian Sea is thicker (Morrison et al., 1999) and more intense than along the Somali coast and reaches values between 0-0.5 ml Oxygen /l between 200-1200 m water depth (Schulte et al., 1999).

**Figure 1.** Map of the Arabian Sea with seasonal surface winds. A. The direction and intensity of the summer monsoon winds darker shading indicates faster wind speeds. The position of core 905 (west) and 131 (east) are identified by white circles. B. The intensity and direction of the winter monsoon winds. Data is from http://iri.ldeo.columbia.edu.
Past records of denitrification in the Arabian Sea

The persistent OMZ in the Arabian Sea is supported by the large flux of organic matter through the water column (Sarma, 2002; Sen Gupta et al., 1984; Wyrtki, 1962) and the supply of O₂ poor intermediate waters from the Southern Ocean (Olson et al., 1993; Sarma, 2002). When O₂ is not available, as in the OMZ, NO₃⁻ is used as the oxidant in the bacterially mediated breakdown of organic matter and N₂ and N₂O are released as by-products (Altabet et al., 2002; Ganeshram, 1996; Ganeshram et al., 2000; Naqvi et al., 1998; Suthhof et al., 2001). This process of denitrification fractionates the stable isotopes of nitrogen, ¹⁴N and ¹⁵N, and leaves the residual nutrient pool relatively ¹⁵N rich. Fractionation of the nitrogen isotopes also occurs during the uptake of NO₃⁻ by phytoplankton (Altabet et al., 1994). Therefore, the degree of nutrient utilization can alter the sedimentary ¹⁵N values. When complete nutrient utilization takes place in the oxygenated waters of the open ocean, where denitrification is not occurring, the under-lying sediments register a ¹⁵N ratio of 4-6 ‰ (Sigman et al., 1999). In upwelling areas where denitrification has occurred in the water column and the ¹⁵N-rich residual NO₃⁻ is brought to the surface, a “heavy” denitrification signal is evident in the sedimentary signal of bulk organic matter (Altabet et al., 1995; Altabet et al., 2002; Ganeshram, 1996; Ganeshram et al., 2000).

Today the most intense water column denitrification is taking place in the intermediate waters of the central and southern Arabian Sea (Morrison et al., 1999) extending southwest from the central Indian coast (Naqvi, 1991). Evidence from modern studies (Brummer et al., 2002) and paleo-records (Altabet et al., 1995; Altabet et al., 2002; Ganeshram et al., 2000; Ivanochko et al., submitted; Suthhof et al., 2001) indicate that denitrification has altered the NO₃⁻ signature of the nutrient pool that is incorporated by phytoplankton in the coastal regions of the Arabian Sea.

Denitrification records from the Omani margin and the Owen Ridge indicate that slight offsets occur between these sites as a result of variable nutrient utilization in the surface waters: the near-shore core beneath the active upwelling centre has values generally 0.5 ‰ lighter (indicating less nutrient utilization) than the offshore core (Altabet et al., 1995; Altabet et al., 2002). However the larger climatic trends associated with past variations in the intensity of the summer monsoon dominate the ¹⁵N records in the northwestern basin, which show a synchronous response to this
variability (Altabet et al., 1995; Altabet et al., 2002). A seasonal study from the coast of Somalia indicates that the extreme heavy sedimentary $\delta^{15}$N values are associated with the post upwelling season from October to February when complete nutrient utilization occurs (Brummer et al., 2002). In August and September when intense upwelling is accompanied by transport of surface waters offshore along eddy margins, the lighter sedimentary $\delta^{15}$N values indicate incomplete nutrient uptake in the surface waters (Brummer et al., 2002). The average of the annual $\delta^{15}$N signal, however, is a reflection of the intensity of the summer monsoon induced upwelling, the resultant flux of organic detritus through the water column and the O$_2$ draw-down in the intermediate waters by respiration (Altabet et al., 2002).

**Setting**

The Somali Basin in the southwestern Arabian Sea is isolated from the Northern Arabian Basin by the Carlsberg Ridge to the northwest and Owen Ridge to the north. These two bathymetric features remove the Somali Basin from the influence of the Indus River discharge and the massive Indus fan that dominates the abyssal sediments of the Arabian Basin. The continental shelf off Somalia is narrow (~50 m) and the slope reaches 1000 m water depth, approximately 70 km offshore. Core 905 collected in 1993 during the Netherlands Indian Ocean Project (NIOP) is located on the Somali margin (10°46'N; 51°57'E) (Figure 1) and is therefore directly impacted by summer monsoon induced productivity. Recovered from a water depth of 1586 m, core 905 is just below the modern oxygen minimum zone. Today, this coastal southwestern site in minimally impacted by winter monsoon and inter-monsoon winds. Therefore, it is ideally located to study past changes in the intensity of the ASSM winds, and the response of both the marine and terrestrial environment.

Core MD76-131 (hereafter 131) was collected from the central western Indian Margin (15°31.8'N; 72°34.1'E) (Figure 1). This core is at the northern extent of the summer monsoon productive region (Divakar Naidu et al., 1992) and is expected to register changes in the summer monsoon related productivity. Core 131 was collected from 1230 m at the base of the modern OMZ and the aragonite lysocline. This location is also highly affected by seasonal rainfall associated with the summer monsoon. Torrential rainfall in the summer months and no precipitation in the winter have resulted in extensive coastal laterites in western India (Nair et al., 1979; Sahasrabudhe et al., 1979). These extremely Fe and Ti-rich precipitate deposits are
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depleted in Si, Ba and Mn and are deposited on the continental slope of India by riverine runoff during periods of strong monsoon activity (see Chapter 7).

**Methods** (see Appendix A)

**Millennial-scale variability in the intensity of the summer monsoon**

Changes in the strength of the monsoon can be identified by downcore changes in proxies of organic productivity (Koning et al., 2001; Prell et al., 1981; Shimmield et al., 1991). Barite (BaSO₄) is thought to precipitate in the supersaturated microenvironment of decaying organic particles and is therefore associated with the flux of organic carbon to the sea floor (Bishop, 1988; Dymond et al., 1992; Ganeshram et al., 2003). Barium is also present in lithogenic detritus which has an average Ba/Al value of 60 x 10⁻⁴ (Wedepohl, 1971). In the core 905 sediments the elevated Ba concentrations are not accompanied by an equivalent increase in Al (Figure 2) suggesting that biogenic Ba is present and is obscuring the signal of lithogenic Ba. Therefore, the Ba/Al ratio, which provides information regarding the non-lithogenic variation of Ba in the sediments, can be used as a proxy of organic flux to the sea floor at this site. The 905 Ba/Al record varies from 600 x 10⁻⁴ during D-O interstadials to less than 100 x 10⁻⁴ during Heinrich Events (Figure 3) indicating that productivity increased during northern Hemisphere warm periods and decreased during cold periods. The lowest values of Ba/Al are below the lithogenic ratio indicating that the detrital Ba concentrations in the Arabian Sea area are lower than average.

**Figure 2.** Ba vs Al values of core 905 (red) and core 131 (blue). The dashed line indicates the average crustal relationship of Ba and Al. The vertical trend of core 905 suggests biogenic Ba is dominating the record. The Ba-depleted values of core 131 reflect the highly weathered soils of western India (see Chapter 7).
The organic carbon measurements (% C$_{org}$) from core 905 vary from 1-2.5 % with the lowest values occurring during Heinrich events (Figure 2). The % C$_{org}$ record strongly resembles the Ba/Al record, within increased % C$_{org}$ values corresponding to increased Ba/Al, despite the former proxy record being subject to variable sedimentary dilution and organic preservation effects (Figure 3). Therefore, the 905 productivity proxies provide clear evidence of millennial-scale changes in productivity off the coast of Somalia. The combined productivity records from the Somali margin are similar to the Northern Arabian Sea colour reflectance records (Schulz et al., 1998), further confirming that millennial changes in the organic carbon contents of the Arabian Sea sediments are related to summer monsoon-driven productivity rather than differential preservation of organic matter and sedimentary dilution effects.

The δ$^{15}$N record from core 905 varies from 4 to 8 ‰ over the past 90 kyr with increased values during Dansgaard Oeschger (D-O) interstadials and minimum values during Heinrich Events and D-O stadials (Figure 3) (see Chapter 4). During marine isotope stage (MIS) 2 and 4, which represent global cold periods when the intensity of the ASSM was diminished, the δ$^{15}$N values of core 905 are low compared to the values during MIS 3 and 5, which represent warmer interglacial periods and times of intense summer monsoon activity. Changes in the core 905 denitrification record coincide with changes in productivity, suggesting that the degradation of organic matter in the intermediate waters is modulating the degree of OMZ dysoxia and therefore the intensity of denitrification (Figure 3). The 905 records support the conclusion of Altabet at el (2002), that millennial-scale variations in basin-wide productivity and denitrification in the Arabian Sea are linked to the intensity of the ASSM winds.

Over the past 90 kyr, the variability of monsoon induced productivity seen in the 905 records is assumed to be synchronous with the Dansgaard-Oeschger variations identified in the GISP2 ice core (see Chapter 3). Increases in productivity occur during interstadials and coincide with increases in denitrification (Figure 3). Periods of decreased ASSM intensity, identified by lowered productivity and minimal denitrification, are associated with stadials. Heinrich Events correspond with the lowest values in the productivity proxies and therefore are apparently coeval with a relative failure of the ASSM (Figure 3).
Figure 3. A reconstruction of the Arabian Sea summer monsoon. A. The Greenland (GISP2) $\delta^{18}$O record indicates temperature variations in the northern polar region. More negative values represent colder temperatures. B. The $\delta^{15}$N record of core 905. Larger values (above 5 ‰) indicate water column denitrification. C. Ba/Al is a proxy of organic productivity. D. The organic carbon record of core 905. E. Changes in the dust content of core 905 are represented by the % Al record.

Regional precipitation records from the nearby Socotra Island (Burns et al., 2003) and the more distant Hulu Cave (Wang et al., 2001) support the 905 records, and indicate that precipitation increased during interstadials alongside increased upwelling, productivity and denitrification. Decreased precipitation both in the western Arabian Sea and in China during stadials and Heinrich Events indicates an overall drying of the region (Burns et al., 2003; Wang et al., 2001). The lithogenic records of core 905 confirm these changes in continental aridity and identify a general
relationship between Heinrich Events in the North Atlantic and periods of increased deflation of terrestrial material in the tropics (Figure 3) (see Chapter 6).

The core 905 productivity, denitrification and aridity records (see Chapter 6) therefore generate a rounded view of the history of ASSM intensity over the past 90 kyr. Changes in winds strength can be deduced from changes in upwelling-induced productivity and the related intermediate water denitrification. Changes in continental moisture can be deduced from variations in the amount of dust reaching site 905 (see Chapter 6). The interpretation of the Indian margin core (131) will rely on the ASSM reconstruction determined from the core 905 productivity records which indicates that increased ASSM intensity occurred during interstadials and decreased intensity occurred during stadials.

**Productivity on the Indian Margin**

Identifying a clear record of organic productivity changes on the Indian slope is not straightforward. However a benefit of the multi-proxy approach is the ability to compare multiple records and discern a common signal. Therefore, in order to understand the changes in organic productivity along the Indian margin measurements of \% C$_{\text{org}}$, \% CaCO$_3$, Sr/Ca, Mn/Al and Ba/Al are discussed.

The organic carbon concentrations of core 131 vary between 1-3.8 % with the lowest values occurring during Heinrich Events (Figure 4). Holocene values of organic carbon are also low. The maximum \% C$_{\text{org}}$ values from these Indian margin sediments are associated with the late last interglacial period, Marine Isotope Stage (MIS) 3, and the last glacial period, MIS 2 (Figure 4). In the \% C$_{\text{org}}$ record from the Indian margin sediments, distinct periods of low productivity, which correspond to periods of reduced summer monsoon intensity, also correspond to large fluctuations (15-70 %) in the \% CaCO$_3$ record (Figure 4). Changes in the \% CaCO$_3$ record are thought to be driven by fluctuations in the depth of the lysocline and therefore variable preservation of aragonitic pteropod tests (Reichart et al., 2004; Singh, 2002). Increases in the core 131 Sr/Ca values coincide with increases in \% CaCO$_3$ and the Sr/Ca general profile closely resembles the \% CaCO$_3$ profile (Figure 4). Therefore, as aragonite has a higher concentration of Sr than does calcite (Reichart et al., 1997), the Sr/Ca record of core 131 supports the hypothesis that variations in aragonite preservation are likely responsible for the CaCO$_3$ spikes that correspond to Heinrich Events. The presence of these distinct CaCO$_3$ bands however, poses a problem in the
analysis of the % $C_{org}$ record. The increase in % CaCO$_3$ is accompanied by a decrease in % $C_{org}$ but whether this is a result of CaCO$_3$ dilution or an independent change in the carbon flux or preservation is not known.

Figure 4. Changes in the CaCO$_3$ preservation and sedimentary oxygenation on the Indian margin. **A.** The Sr/Ca record highlights enhanced aragonite concentrations. **B.** The CaCO$_3$ record of core 131. **C.** Increased Mn/Al values indicate oxic sedimentary conditions. **D.** The record of organic carbon for core 131. **E.** The denitrification record of core 131. Increased values over 5 ‰ indicate denitrification in the water column.

The calculation of the “carbonate free” % $C_{org}$ produces a record with peaks and minimum values that correspond to the original % $C_{org}$ record (Figure 5). This indicates that the decreases in % $C_{org}$ corresponding to HE are not solely a dilution signal resulting from the increase in % CaCO$_3$ through enhanced aragonite preservation. Additionally, by taking the assumption of synchronicity to an extreme, a
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A high-resolution sedimentation rate for core 131 was created by tying the entire core 131 record directly to the GISP2 \( \delta^{18}O \) record by matching as many peaks and troughs as possible. The mass accumulation rate of \( C_{\text{org}} \) was then calculated and shows that the accumulation rate of organic carbon decreases during HE when the summer monsoon intensity was diminished. Calvert et al, (1995) show that carbon preservation on the Indian continental slope is not directly related to the position of the OMZ or the concentrations of oxygen in the bottom waters. This is corroborated by Cowie et al (1999) who focussed on sediments from the Pakistani margin. Therefore variable organic production in the surface waters is more likely to determine the concentration of \( \% \) \( C_{\text{org}} \) in these sediments than variable preservation controlled by changes in the intensity of the OMZ. Though the \( \% \) \( C_{\text{org}} \) record on its own may be questioned, the carbonate-free and MAR calculations suggest that the \( \% \) \( C_{\text{org}} \) profile is not a record of \( \text{CaCO}_3 \) dilution and does reflect a decrease in organic productivity during periods that coincide with Heinrich Events (Figure 5). An additional event registering low \( \% \) \( C_{\text{org}} \) occurs at 38 kyr and does not correlate with a HE (Figure 5).

![Figure 5](image-url)

**Figure 5.** Productivity variations on the Indian margin. **A.** The record of \% organic carbon. **B.** The calculation of “carbonate-free” organic carbon values allows the impact of sedimentary dilution by \( \text{CaCO}_3 \) to be assessed. The similarity between this record and the record in A. indicates that dilution is not driving the changes evident in
the organic carbon record. C. The calculation of mass accumulation rate (MAR) indicates changes in the accumulation of organic carbon in the sediments.

The strong correlation between the records of past productivity, denitrification, and continental aridity determined from core 905 indicates that the summer monsoon has dominated the western basin over the past 90 kyr. The influence of the winter monsoon is not evident in the Somali margin records and the relationship between productivity, denitrification and continental aridity has remained constant over this time period. In contrast, the % $C_{\text{org}}$ record and the calculations of % $C_{\text{org}}$ (carbonate free) and MAR $C_{\text{org}}$ from the Indian margin core 131 indicate that during the last glacial period, and possibly during MIS 4, productivity on the Indian Margin remained high even though the intensity of the summer monsoon diminished.

Today, the southern coast of Indian experiences high productivity during the summer monsoon season (Banse, 1987; Divakar Naidu et al., 1992) and the northeastern Indian coast experiences a secondary productivity bloom during the winter monsoon season (Banse, 1987; Honjo et al., 1999; Madhupratap et al., 1996; Schulte et al., 1999). Site 131 is located between the high productivity areas both to the north and to the south. Therefore, the sustained high productivity seen in the core 131 records during glacial periods, when the summer monsoon intensity diminished, may reflect the influence of the secondary bloom in the northeastern basin that is associated with the winter monsoon-induced convective mixing of the surface waters (Madhupratap et al., 1996). If this is the case, the paleo-productivity record of site 131 suggests that during glacial periods, the influence of the secondary winter bloom was large enough to compensate partly for the decrease in the summer bloom related to diminished summer monsoon induced-upwelling.

High productivity on the Indian margin during glacial periods, sustained by winter monsoon mixing, is supported by the heavier $\delta^{15}$N values of the Indian margin core compared to values of the Somali margin core during MIS 2 and 4. The 905 $\delta^{15}$N values during the last glacial drop from interglacial values of approximately 7 ‰ to 5.5 ‰ suggesting that denitrification was not influencing these waters at this time. In contrast, during the last glacial period the core 131 $\delta^{15}$N values remain at 6.5 ‰, values indistinguishable from those of the late MIS 3 (Figure 6). During MIS 4, core 905 registers values below 4 ‰ whereas core 131 averages 5.5 ‰. As well, though the two $\delta^{15}$N records are very similar during the MIS 3 interglacial period, when the
intensity of the summer monsoon was elevated, the $\delta^{15}$N profiles of core 905 and 131 differ in structure during the glacial periods. An increase in the winter monsoon strength, as indicated by the organic carbon records of core 131, would explain the offset between the $\delta^{15}$N values and the profile differences between core 131 and 905 during the glacial periods.

**Figure 6.** Comparing the productivity records of the Somali and Indian margins. **A.** The Indian margin denitrification record. **B.** The Somali margin denitrification record. Dashed grey lines are to accentuate the comparisons made in the text. **C.** The Indian margin record of sedimentary organic carbon. **D.** The Somali margin record of sedimentary organic carbon. **E.** The Ba/Al record of the Indian margin. **F.** The Ba/Al record of the Somali margin.
Additional discrepancies occur between the δ¹⁵N records from the western and eastern Arabian Sea. Overall the δ¹⁵N values determined on the eastern margin are 1 ‰ higher than the values determined on the western margin. As well, the δ¹⁵N values of core 131 during MIS 4 do not drop as severely as the core 905 values and remain constant at 5.5 ‰ unlike the gradual increase seen in the 905 δ¹⁵N profile at this time (Figure 6).

These discrepancies may be a result of differential nutrient utilisation. Intense coastal upwelling, which is concentrated in the south in the summer months and in the north in the winter months, does not directly influence the central Indian margin sediments. The δ¹⁵N values of the Owen Ridge site in the western basin that is offset from the upwelling cell are heavier than those of the Oman site, which is located directly beneath the upwelling center. This has been explained as a result of incomplete nutrient utilisation in the upwelling centre and the advection of heavy NO₃⁻ to the more distant site (Altabet et al., 1995). During the post monsoon season when the surface currents reverse and the southern waters are advected north, site 131 may be flushed with relatively heavier NO₃⁻ as a result of incomplete nutrient utilization in the southern region. When the winter monsoon is strong, this same argument can be made in reverse, where site 131 is flushed with heavy NO₃⁻ in the spring season at the onset of the anti-cyclonic circulation.

Alternatively, the heavier δ¹⁵N values at site 131 may be a reflection of sluggish eastern boundary circulation resulting in a more intense oxygen minimum zone in the eastern basin. On the Somali margin, O₂ concentrations in the OMZ are approximately 20 µM (0.48 ml/l) (de Wilde et al., 1997), in the northern basin near Pakistan OMZ O₂ concentrations range from 0-0.5 ml/l (Schulte et al., 1999) and on the southern Indian Margin O₂ concentrations are effectively 0 between 200-800 m (Naqvi et al., 1998). This progressive decrease of O₂ from west to the east suggests that more intense denitrification is occurring on the eastern margin and the δ¹⁵N values of the eastern margin sediments would be expected to register heavier values on average. Today the most intense denitrification in the Arabian Sea occurs just northwest of site 131 (Morrison et al., 1999; Naqvi, 1991). The 1 ‰ difference between the range of values in core 905 from the Somali margin (3.8-8 ‰) and those of the Indian margin core 131 (4.2-9 ‰) can be explained simply by the progressive intensification of the OMZ from west to east.
Finding an additional proxy of productivity to corroborate the % C\textsubscript{org} record is not trivial. In general the record of Ba/Al is a robust proxy of organic productivity as long as sulphate reduction is not occurring in the sediments (Dymond et al., 1992). However the influx of Ba-depleted sediments from the local Indian continent means that in the eastern Arabian Sea, the overall concentrations of Ba are low and that a lithogenic Ba/Al background cannot be accurately determined (see Chapter 7). The comparison of Ba to Al (Figure 2) in the western Arabian Sea sediments (core 905) clearly shows the non-linear relationship of Ba and Al expected when biogenic-Ba dominates over lithogenic Ba. In contrast, the eastern basin sediments of core 131 are depleted in Ba below crustal values suggesting that the enrichment of biogenic-Ba though still possible, cannot be extreme. Additionally the 131 sediments show a general increase with Al although there is a large degree of scatter in the data. This scatter may reflect changes in the production of Ba-depleted sediments, the transport of these sediments to site 131, changes in biological productivity and sedimentary redox conditions, all parameters that determine changes in the Ba concentrations. Despite these complicating factors, the Ba/Al profile of core 131 does generally resemble changes in % C\textsubscript{org}, particularly the increase during the last glacial maximum and the decrease in early MIS 3 (45-55 kyr) (Figure 6). As well, all of the HE except HE 6 are associated with decreased Ba/Al values.

In summary, on the Indian continental slope the % C\textsubscript{org} record appears to produce a robust history of changes in the organic productivity. The Indian margin % C\textsubscript{org} record generally follows the summer monsoon reconstruction provided by the Somali margin proxies of productivity and denitrification. Large decreases in the Indian margin % C\textsubscript{org} profile correspond to Heinrich Events, periods of decreases summer monsoon activity. However, during the last glacial period, productivity on the Indian margin appears to have remained high and MAR calculation of C\textsubscript{org} suggest that the glacial periods MIS 2 and 4 were relatively more productive than the interglacial periods. The Ba/Al record and the $\delta^{15}$N records both support the conclusions that productivity on the Indian margin remained high or was elevated above interglacial values during glacial periods and that HE 1-5 are expressed as periods of low productivity.
Ventilation and the Winter Monsoon

The changing preservation of aragonite in the 131 sediments however, does imply a variation in the sedimentary oxygenation conditions over time. Variations in sedimentary oxygenation can be identified by the concentration of Mn in the sediments (Calvert et al., 1996) In suboxic sediments, Mn (IV) is reduced to Mn (II) and is lost from the sediments (Calvert et al., 1996). Therefore elevated Mn concentrations in marine sediments suggest that deposition occurred under oxic conditions (Calvert et al., 1996). The lateritic soils of central and southwestern India are depleted in Mn (Nair et al., 1979; Sahasrabudhe et al., 1979), therefore the concentrations of Mn, with respect to Al, that are transported to the continental slope by local riverine runoff are low (see Chapter 7). Despite the low background concentrations, increases in the Mn/Al profile of core 131 are evident and occur during periods of decreased % C<sub>org</sub> (Figure 4). These increases in Mn/Al likely identify occasions when less reducing sedimentary conditions existed.

The degradation of organic matter consumes O<sub>2</sub> and produces CO<sub>2</sub>, the latter of which is corrosive to and initiates the dissolution of CaCO<sub>3</sub> (Schulte et al., 2003; Wenzhöfer et al., 2001). Therefore, the preservation of aragonite in the core 131 sediments may be mediated by the flux of organic matter to the sediments and the subsequent O<sub>2</sub> consumption as it is remineralized. The “mirror image” relationship between Mn/Al and the % C<sub>org</sub> record further suggests that the flux of organic matter to the sediments is mediating the bottom water oxygen conditions.

Reichart et al, (2002) and (2004) propose that ventilation in the northeastern basin results from increased winter monsoon-induced deep convective mixing and is responsible for the replenishment of O<sub>2</sub> in the intermediate waters during HE. Unfortunately, there is no geochemical evidence in the core 131 records to support this conclusion. Increased winter monsoon winds do not appear to be depositing sediments at the 131 site that are distinct and identifiable as having a northern source (see Chapter 8). The organic carbon records of core 131 also do not support this conclusion. Heinrich events correspond to minimum values of % C<sub>org</sub>, % C<sub>org</sub> (carbonate-free) and MAR C<sub>org</sub> (Figure 5) and a secondary productivity bloom associated with deep convective mixing in the northeastern basin (Banse, 1987; Honjo et al., 1999) is not identifiable as sustaining or elevating the productivity records of core 131 during HE. The variations in sedimentary oxygenation, evident by increased Mn/Al values, appear to be driven by changes in the flux of organic matter to the
sediments, the preservation of which is not controlled by the intensity the OMZ (Calvert et al., 1992; Calvert et al., 1995; Cowie et al., 1999). Finally, the \( \delta^{15}N \) values seen on the Indian margin do appear to be elevated above the Somali margin values, however the 1 ‰ offset can be explained by other mechanisms evident today, such as the eastern intensification of the OMZ.

Conclusions

The dominance of the Summer Monsoon, which determines coastal upwelling, productivity, intermediate water denitrification and continental aridity in the Arabian Sea is evident from a reconstruction of a 90 kyr history from a Somali margin sediment core. Millennial-scale variations in the Arabian Sea summer monsoon relate to Dansgaard-Oeschger temperature variations measured from the Greenland ice core GISP2. A second core from the Indian margin indicates that these sub-orbital variations are a basin-wide signal where increased denitrification corresponds to interstadial warm periods and decreased denitrification corresponds to cold stadial periods.

The productivity records (% C\textsubscript{org}, % C\textsubscript{org} (carbonate free), MAR C\textsubscript{org}, and Ba/Al indicate periods of minimal summer monsoon strength occur during Heinrich Events. There is no evidence from the Indian or the Somali margin that the intensity of the winter monsoon increased specifically during HE. Although the sedimentary oxygenation increased during these events, this is explained by the decreased flux of organic material to the sediments. However the productivity and \( \delta^{15}N \) values of the Indian margin core do suggest within the glacial non-Heinrich periods, MIS 2 and 4, sustained or elevated intensity of the winter monsoon occurred. During glacial periods, local variations in denitrification and productivity are identifiable in the paleo-records whereas during the last interglacial, when the summer monsoon was strong, the regional signal dominates both cores.

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