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Geographical extent of denitrification in the Arabian Sea in relation to some physical processes

Arabian Sea
Denitrification
Primary production
Surface circulation
Winter convection

Mer d'Oman
Dénitrification
Productivité primaire
Circulation superficielle
Convection hivernale

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ABSTRACT

Utilizing all the available data, the distribution of nitrite at the secondary nitrite maximum is studied to delineate the boundaries of the denitrification zone and to understand some of the processes that control the extent of denitrification in the Arabian Sea. Nitrite distribution shows little correspondence with primary productivity, and the three major sites of seasonal upwelling appear to be located outside the zone of intense denitrification. This distinguishes the Arabian Sea from the other two major oceanic denitrification sites, located in the Pacific Ocean. The relationship between nitrite and nitrate deficit suggests that the distribution of the former effectively reflects the extent of denitrification. The locus of the most intense denitrification appears to extend southwest from the shelf break off Gujarat. In the northernmost and western parts of the Arabian Sea, denitrification seems to be inhibited by the supply of oxygen from the surface to subsurface layers due to the convective overturning of surface waters during the winter. The northward flow of warm, low-salinity waters from the equatorial region, however, maintains strong stratification in the eastern and central Arabian Sea. It is suggested that the development of reducing conditions in the Arabian Sea may be closely related to this feature.

Intense cooling close to the coast of Gujarat, especially within the Gulf of Kutch, may lead to the formation of a lower-salinity water which may advect to depths of ~200 m. This provides a mechanism for the injection of appreciable quantities of labile dissolved organic carbon (DOC) into the oxygen-minimum layer and, in conjunction with the high horizontal diffusivity in the Arabian Sea, could account for the observed lack of correspondence between denitrification intensity and primary productivity. The results are examined in the light of available information on the paleoceanography of the region. It is postulated that the absence of low-salinity waters off India, more intense evaporation, and lower oxygen demand (due to the lower overall fertility and decreased input of DOC associated with the advection of shelf water) might all combine in producing a better glacial oxygen balance at mid-depth.

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RÉSUMÉ

Limite géographique de la dénitrification en mer d'Oman en relation avec les processus physiques

Nous avons étudié la distribution de nitrite en mer d'Oman, afin de délimiter la zone de dénitrification et de comprendre les processus qui gouvernent son étendue. Ce travail utilisdes données originales ainsi que toutes celles disponibles dans la littérature. La distribution des nitrites montre peu de relations avec la production primaire. Les trois principaux sites d'upwelling saisonnier semblent être localisés en dehors de la zone d'intense dénitrification. Ceci distingue la mer d'Oman des deux autres zones d'intense dénitrification situées dans l'Océan Pacifique. La relation entre les nitrites et le déficit en nitrates suggère que la distribution des nitrites traduit bien la limite de dénitrification. L'origine de la zone d'intense dénitrification semble être localisée au sud-ouest de la bordure du plateau de Gujarat. Dans les régions les plus au nord et à l'ouest de la mer d'Oman, la dénitrification semble être inhibée par un important flux d'oxygène. Ce gaz est transporté de la surface vers les couches de sub-surface par la convection hivernale. Cependant l'écoulement vers le nord des eaux chaudes de faible

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salinité provenant des régions équatoriales maintient une forte stratification dans l'est et le centre de la mer d'Oman. Nous pensons que ceci favorise le développement des conditions réductrices en mer d'Oman. Le refroidissement intense près de la côte de Gujarat, en particulier dans le golfe de Kutch, est peut-être responsable de la formation d'eaux à faible salinité qui, par advection, peuvent plonger à des profondeurs de l'ordre de 200 m. Ceci permet l'injection de grandes quantités de carbone organique dissous labile dans la couche de concentration minimale en oxygène. Ce processus, ainsi que la forte diffusivité horizontale en mer d'Oman, peuvent être responsables du manque de relations entre l'intensité de dénitrification et la productivité primaire. Les résultats ont également été confrontés aux données de paléo-océanographie disponibles pour cette région. Nous calculons un nouveau bilan de l'oxygène à mi-profondeur pour l'océan glaciaire. Pour ce faire, il est important de tenir compte de l'absence d'eaux de faible salinité au large de la côte indienne, d'une évaporation plus intense et d'une plus faible utilisation d'oxygène due à une productivité réduite et à une diminution de l'apport en carbone organique dissous.

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INTRODUCTION

The Arabian Sea is one of the three major oceanic denitrification sites, accounting for roughly one-third of global water-column denitrification (Naqvi, 1987). However, the geographical boundaries of the Arabian Sea denitrification zone have not so far been clearly demarcated. Previous works have shown that the process ceases south of about 12-14°N latitude (Naqvi, 1987; and references therein). The southern limit is perhaps determined by an increase in the upward flux of oxygen associated with the upwelling of deep water, coupled with a southward decrease in particle flux (Somasundar and Naqvi, 1988). Implicit in these reports has been the assumption that denitrification occurred everywhere north of this limit. This in turn stemmed from an inadequate understanding of the processes controlling the development and maintenance of reducing conditions at mid-depth. That is, it had been believed that the acute deficiency of dissolved oxygen was due to a combination of subsurface water stagnation and a high rate of primary production (Wyrtki, 1973; Qasim, 1982; Sen Gupta and Naqvi, 1984), which implied a northward intensification of the oxygen minimum. However, recent results have shown that the intermediate waters in the northern Arabian Sea might be renewed quickly, on time scales of a few years, possibly months (Somasundar and Naqvi, 1988). The available data also suggest that spatial changes in denitrification intensity may not be consistent with the trends expected from primary productivity (Naqvi, 1986; 1987). A re-examination of the geographical extent of denitrification in the Arabian Sea is thus called for.

Besides determining the geographical limits of the mid-depth reducing environment, the present communication also focuses on the anomalous lack of correlation between primary productivity and the intensity of reducing conditions. It underlines the role of vertical stratification, which seems to be closely linked with the surface circulation, as well as that of the dissolved organic carbon (DOC) injected into the oxygen-deficient layer through the formation of dense water on the inner shelf, in the development of reducing conditions at intermediate depths.

EXTENT OF DENITRIFICATION IN RELATION TO PRIMARY PRODUCTIVITY

In order to delineate the denitrification zone, a secondary nitrite maximum was sought in all the data available at the Indian National Oceanographic Data Centre (INODC). There were a total of 674 deep stations located north of latitude 10°N, where nitrite observations had been made. This data base comprised almost all the data generated during the International Indian Ocean Expedition (IIOE), and those taken subsequently during numerous cruises of INS *Darshak*, R/V *Gaveshani* and ORV *Sagar Kanya* as well as a cruise of R/V *Atlantis II*. The maximum observed concentration at each station was selected to calculate the averages for each 1-degree square. These are plotted in Figure 1. The data set represents an uneven coverage of the region in space and time. For instance, many more observations have been made during the northeast (NE) monsoon than in the southwest (SW) monsoon season, especially in the northwestern sector. Also, the eastern and central parts have been more intensively covered during numerous recent cruises. Given the marked seasonality in the composition of the oxygen-deficient waters especially along the margins (Naqvi *et al.*, 1990), one may question the wisdom of lumping together data generated during various seasons. Paucity of observations in the northwestern Arabian Sea during the SW monsoon does introduce a certain bias; hence the conditions depicted in Figure 1 might be more representative of the NE monsoon. Otherwise, the figure should outline the maximal horizontal domain of the denitrifying environment fairly well.

As stated earlier, it was assumed in previous studies that denitrification occurred everywhere in the northern

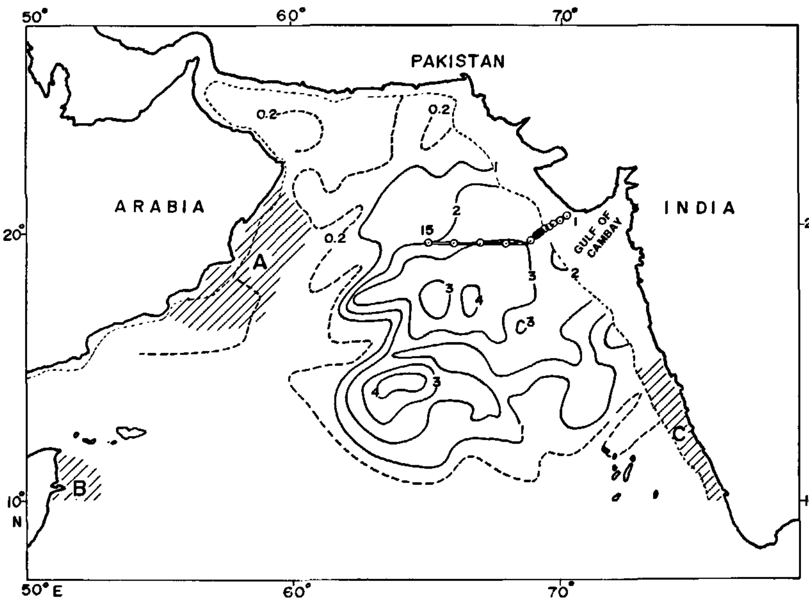

Figure 1

Distribution of nitrite (μM) at the secondary maximum averaged for each 1° square using all the available data. Hatched areas represent zones of upwelling off Arabia (A), Somalia (B) and southwest India (C). Extensions of zones B and C south of latitude 10°N are not shown. The 200 m depth contour and the locations of stations comprising the sections presented in Figure 8 are also shown.

Arabian Sea. Figure 1 shows that such is not the case: low nitrite concentrations, very often close to the detection limit, are observed in the northernmost and western Arabian Sea. In the present study, the denitrification zone was operationally taken to be bounded by the 0.2 μM NO_2^- contour (very few "detectable" nitrite concentrations were below this value), and the total area of the Arabian Sea affected by denitrification was computed as 1.37×10^6 km^2. This is about 30% smaller than the previous estimate (1.95×10^6 km^2 in Naqvi, 1987).

Figure 2 shows the distribution of column productivity averaged for each 1-degree square based on all the data available at the INODC. Again, the data base included the IIOE results (Babenerd and Krey, 1974), and a large amount of more recent data collected on board *Darshak*, *Gaveshani* and *Sagar Kanya*. Figures 1 and 2 exhibit very little similarity. Indeed the three upwelling centres located off Arabia (zone A), Somalia (zone B, only partially shown in Fig. 1), and southwest India (zone C, partially shown) appear to experience very mild reducing conditions, if at all. Zone C is of particular interest because it is perhaps the only area of the Indian Ocean with a typical (although seasonal) eastern boundary upwelling environment, *i.e.*, coastal upwelling, an equatorward surface flow and a poleward undercurrent (Shetye *et al.*, 1990). Interestingly, however, this zone experiences no denitrification during

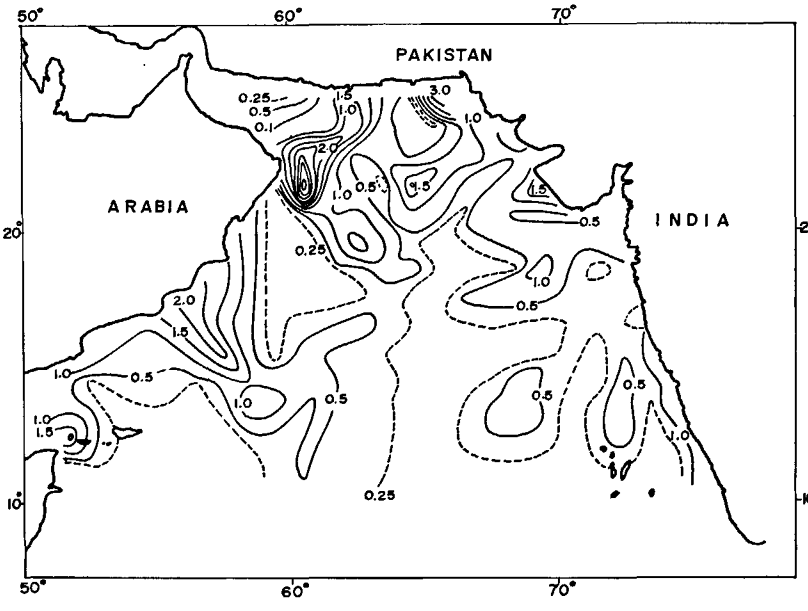

Figure 2

Distribution of primary production ($g \cdot C m^{-2} d^{-1}$) averaged for each 1° square using all the available data.

the SW monsoon when upwelling occurs, while mildly reducing conditions develop during the NE monsoon (Naqvi *et al.*, 1990).

In order to ascertain whether nitrite distribution at the secondary maximum (Fig. 1) reflects spatial changes in denitrification, we must examine the relationship between nitrite and nitrate deficit [the difference between "expected" nitrate, estimated following Naqvi *et al.* (1990), and the sum of observed nitrate and nitrite concentrations]. The two are generally linearly related (Fig. 3), the large scatter probably reflecting the known dependence on environmental conditions of the relative rates of nitrate and nitrite reductions by denitrifying bacteria (Anderson *et al.*, 1982; and references therein). One of these is the availability of organic matter. It has been shown experimentally that the bacteria favour the reduction of nitrate to nitrite under organic-rich conditions. However, when organic substrate levels are low, nitrite reduction is the favoured pathway (Ozretich, 1976). Within oxygen-deficient zones, the ratio of nitrite concentration to nitrate deficit is thus expected to decrease as the depth increases, due to a decline in the availability of organic carbon. In order to account for this effect the following empirical relationship has been assumed:

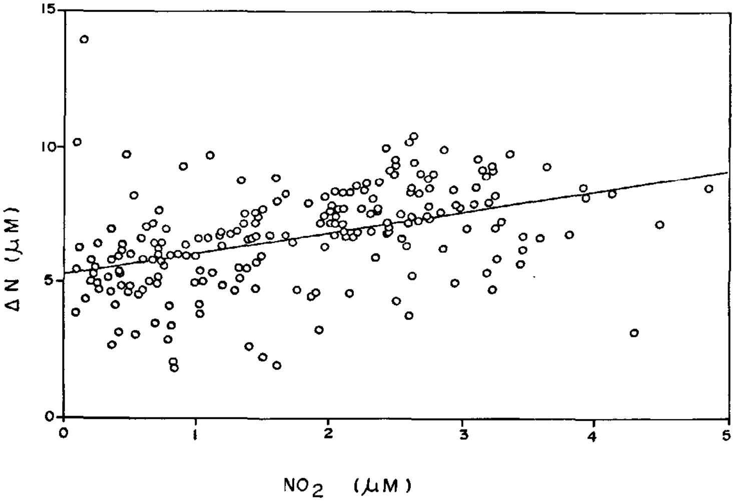

Figure 3

Relationship between nitrate deficit (ΔN) *and nitrite* (NO_2).

(1) $NO_2^- = a + b\Delta N + ce^{-dZ}$,

where ΔN is the nitrate deficit and Z the depth; a, b, c and d are constants.

A typical example of curve-fitting to the observed nitrite profile is given in Figure 4. Best-fit values of coefficients a, b, c and d were obtained from a combination of analytical and numerical procedures. That is, d was varied numerically to arrive at the set of constants for which the sum of squares determined analytically was minimum.

The exact physical significance of the coefficients is difficult to understand, although these are expected to be dependent on factors such as circulation, export production and bacterial population. This empirical model was formulated to determine whether the southward shoaling of the secondary nitrite maximum (Naqvi and Qasim, 1983) could be responsible for the elevated nitrite concentrations in the south-central Arabian Sea (Fig. 1). Using the best-fit coefficients given in Figure 4 and assuming other things to be equal, it could be calculated that an upward shift in the depth of nitrite maximum from 300 to 250 m would raise the nitrite levels by <0.5 μM. However, considering that the peak nitrite concentrations are found in areas where the column production is lower by a factor of at least 4 in comparison with the productive marginal zones (Fig. 2), an increase of this magnitude should be more than compensated by the decrease caused by a lower particle flux. Therefore, it is reasonable to infer that the high nitrite ridge extending in a southwesterly direction from the shelf break off Gujarat constitutes the locus of most intense denitrification.

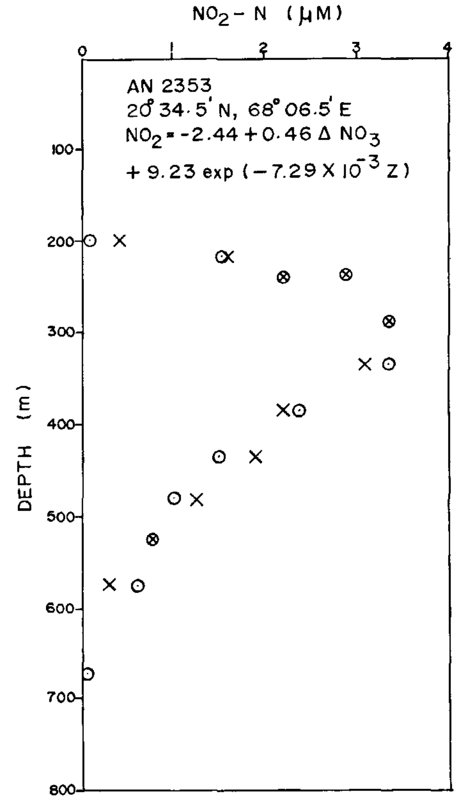

Figure 4

Model fit (crosses) to nitrite observations (circles) at station AN2353.

Thus the absence of significant denitrification beneath the most productive coastal upwelling zones, the NE-SW orientation of the axis of most vigorous denitrification, and lack of a positive correlation between the secondary nitrite maximum and primary production (Fig. 5) distinguish the Arabian Sea from the denitrification sites of the Pacific Ocean (Cline and Richards, 1972; Codispoti and Packard, 1980). This anomaly could be due to a more effective re-oxygenation of intermediate waters beneath the productive zones and/or a different, possibly additional, mode of input of biodegradable organic matter to the subsurface layers of the Arabian Sea. Both of these possibilities are examined in some detail in the following sections.

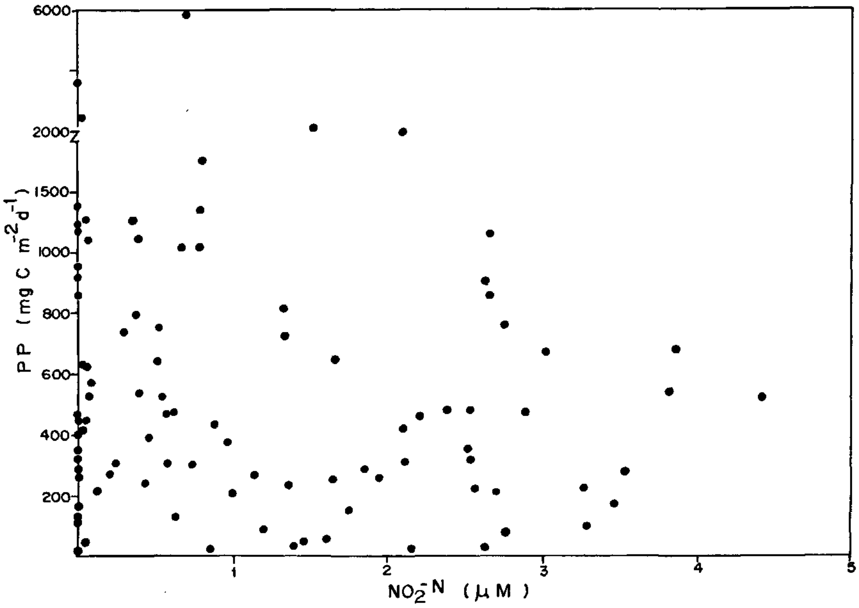

Figure 5
Plot of nitrite (NO_2) *vs primary production* (*PP*) *north of* 12°N *latitude.*

SURFACE CIRCULATION AND WINTER CONVECTION

It has been suggested that the poleward undercurrent observed off the SW coast of India during the SW monsoon season could be the dominant mechanism for the supply of oxygen to the oxygen-poor waters, thereby suppressing denitrification in the eastern Arabian Sea (Naqvi *et al.*, 1990). However, an undercurrent is a common feature of all the eastern boundary environments (McCreary, 1981). For example, a similar, probably more intense, undercurrent is also a source of oxygen to the oxygen-deficient zone off Peru (Brockmann *et al.*, 1980). However, the most vigorous denitrification there still occurs close to the continental margin (Codispoti and Packard, 1980). Therefore, additional mechanisms must be sought to account for the probable more effective re-oxygenation of subsurface waters along the boundaries, particularly in the northern and western Arabian Sea.

Banse (1984) observed that the oxygen levels within the temperature range 20-25°C were much higher (by up to 2 cm^3 dm^{-3}) off Pakistan than off Gujarat. He attributed this to the winter cooling of shelf waters in the northern region which could produce a well-ventilated salinity maximum at about 25 σ_t surface, and concluded that such a mechanism might lead to con-

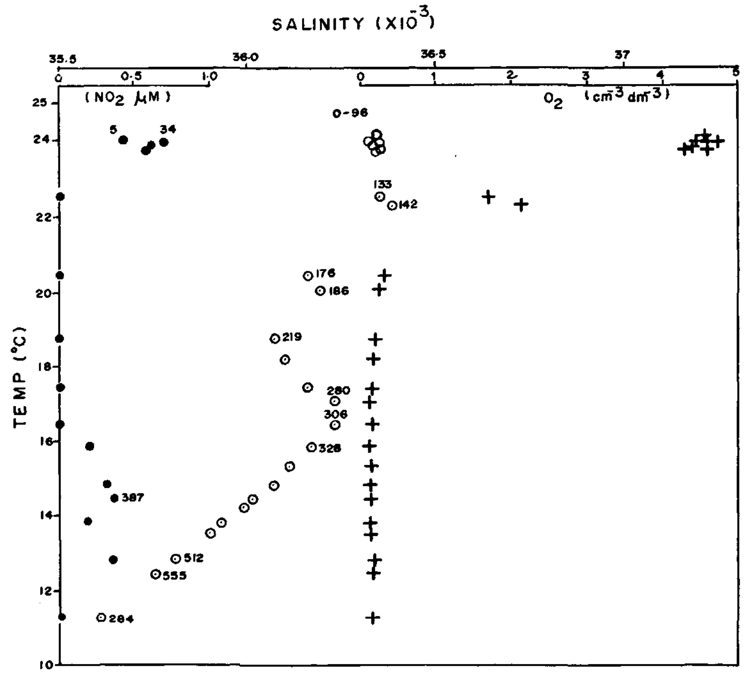

Figure 6
Variations in salinity (open circles), oxygen (crosses) and nitrite (solid circles) with temperature during winter at a station off Karachi.

siderable aeration of the upper parts of the thermocline.

In addition to the above sinking (advection) of denser water over the northern shelf, considerable re-oxygenation may also occur as a result of convective overturning (vertical mixing) in the open ocean. Data from a station occupied by *Atlantis II* (Lat. 24°12.2′N; Long. 64°42.6′E; date of sampling 20 January 1977) provide firm evidence for such mixing (Fig. 6). Marked surface cooling (sea surface temperature ~24°C) at this site resulted in a deep (~100 m) isothermal, isohaline layer. A single, well-defined salinity maximum within the upper thermocline was not observed at this station, although the thermohaline structure and the oxygen profile did exhibit finer features (*e.g.* at 142 m) which could have resulted from advection from the shelf. The weak density gradients resulting from surface cooling and the associated vertical mixing are expected to lead to an enhanced flux of oxygen to the waters below the thermocline. This apparently makes up for the expected higher oxygen demand owing to the higher rates of biological production (Banse, 1987) since denitrification appears to be inhibited in the upper layers and is confined to a thin zone beneath the core of the Persian Gulf water (Fig. 6).

As pointed out by Banse (1984; 1987), winter convection occurs at much lower latitudes in the North Indian Ocean than in the Pacific and the Atlantic oceans, primarily because of the landmass which bounds the Arabian Sea in the north at ~25°N. It may also be closely controlled by the surface circulation. Generally counter-clockwise surface circulation during the NE monsoon maintains low (<25°C – Wyrtki, 1971) surface temperatures in the northern and western Arabian Sea, favouring vertical mixing. On the other hand, the northward flow of warm (>27°C – Wyrtki, 1971), low-salinity equatorial water in the eastern Arabian Sea probably leads to strong stratification which inhibits vertical mixing.

In order to demonstrate the effect of surface circulation on the subsurface water composition, we shall examine the distribution of several properties in a vertical section (Figs 7 and 8), utilizing data generated during consecutive SW and NE monsoon seasons (Naqvi *et al.*, 1990). Marked seasonal changes in hydrochemical conditions are evident, especially pronounced near the continental margin. The core of the northward flowing equatorial water is represented by the high temperatures (>27°C) and low salinities ($<36\times10^{-3}$) over the shelf break (Fig. 7). At this latitude (21°N), however, this flow occurs as a strong jet, possibly due to vertical mixing over the shelf (Shetye *et al.* 1991). The strong stratification is reflected in the surface nutrient concentrations, which are lower in the vicinity of the coast than in the waters lying further offshore. The northern limit of this zone of strong vertical stratification may be marked by a thermal front oriented almost perpendicular to the coast off the Gulf of Kutch during the NE monsoon (Wyrtki, 1971).

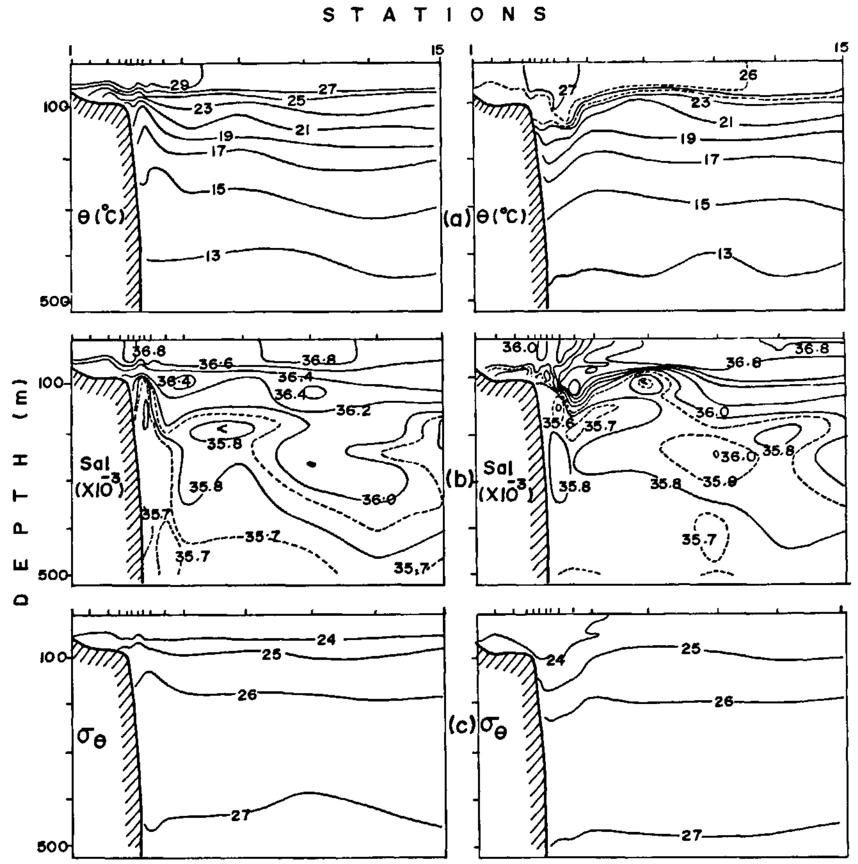

Figure 7

Vertical sections of temperature (a), salinity (b) and sigma θ (c) along the transect shown in Figure 1. The left and right panels depict conditions existing during the successive southwest and northeast monsoon seasons respectively.

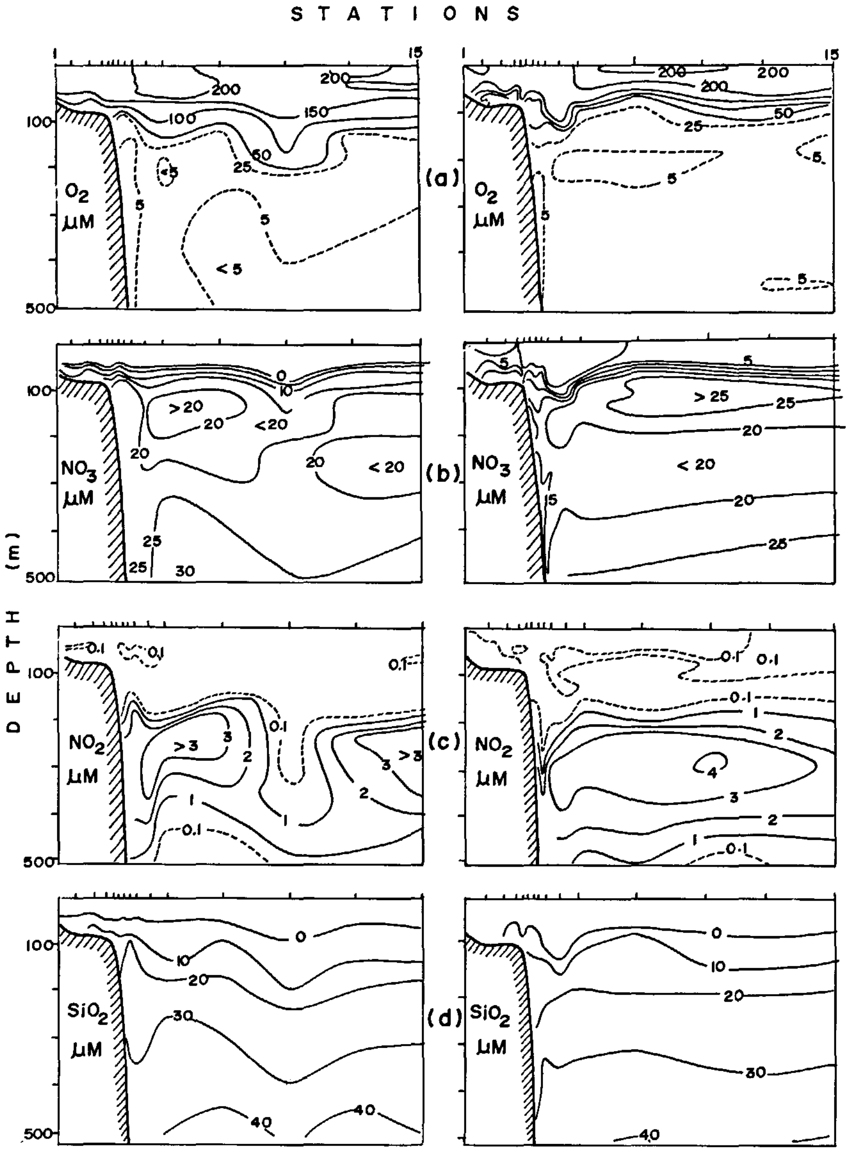

Figure 8

Vertical sections of oxygen (a), nitrate (b), nitrite (c) and silicate (d) as in Figure 7.

Outside the zone of strong vertical stratification (along the northern and western boundaries), denitrification seems to be inhibited by the oxygen supply through diffusion from the surface layer. This suggests that the advection of warm, low-salinity equatorial water in the eastern and central parts (which minimizes the oxygen exchange between the surface and subsurface layers) may hold the key to the development of reducing conditions in the Arabian Sea. It would appear that the re-oxygenation of subsurface waters through supply from the surface layer may be much more important than realized so far, and may well be the single most important factor controlling spatial changes in denitrification in the region.

FORMATION OF DENSE WATER ON THE CONTINENTAL SHELF – A SOURCE OF DOC TO THE OXYGEN-DEFICIENT LAYER?

The cold, dry continental winds blowing from the north or northeast during the winter cause an intense heat loss from the sea near the coasts off Gujarat and Pakistan. Consequently, pockets of cold water are formed in some shallow regions. Three such sites where the cooling is particularly intense, identified with the aid of satellite-derived data, are the inner shelf off Pakistan and the gulfs of Cambay and Kutch (Shetye *et al.*, in prep.). In the Gulf of Kutch, for example, winter cooling lowers surface temperatures to ~16°C (Dhawan, 1970), perhaps leading to the production of dense water which may advect into the oxygen-minimum layer beyond the shelf, accounting for the salinity minimum at ~200 m depth (Fig. 7).

Nutrient data provide support for sinking of water from the shelf (Fig. 8 *b-d*). However, the impact on dissolved oxygen levels is not very large; this could reflect high consumption rates as well as the intermittent (episodic) formation of the watermass.

Nevertheless, the observed lower denitrification intensity close to the continental margin may be partly due to the re-oxygenation associated with the advection from the shelf.

Perhaps a potentially more important aspect of the above possibility is that it provides a mechanism for the transport of DOC from a productive zone to the subsurface water, a matter whose significance is due to the growing realization of the importance of DOC in oceanic biogeochemical cycling [*see* Toggweiler (1989) for a review]. On the basis of measurements employing a new method involving high temperature catalytic oxidation, Sugimura and Suzuki (1988) have demonstrated that oceanic DOC is perhaps much more labile than so far believed. Their results suggest that the bulk of deep-sea respiration might be fuelled by DOC. Following a high temperature wet oxidation method but with a different catalyst (copper and cobalt oxides), Kumar *et al.* (1990) found DOC to behave non-conservatively in the Arabian Sea as well. However, the relationship between DOC and apparent oxygen utilization (AOU) observed by these authors was weak, and only a small fraction of the oxygen consumption could be attributed to the DOC changes ($\Delta DOC/\Delta AOU = -0.06$ as compared to -0.9 reported by Sugimura and Suzuki, 1988). Interestingly, DOC seemed to be better correlated (negatively) with the nitrate deficit, indicating that denitrification could be fuelled by DOC. Kumar *et al.* (1990) concluded that the cycling of DOC is much faster within the oxygen-depleted, denitrifying zone than in the oxidizing environment of the Arabian Sea. An important implication of these results is that, given the short renewal time of the denitrifying layer (1.6-3. a – Somasundar and Naqvi, 1988), labile DOC may not be characterized by long regeneration times as assumed earlier (*e.g.*, ~200 a – Toggweiler, 1989).

In their analysis, Kumar *et al.* (1990) only considered the production of DOC from particulate matter. As indicated earlier, the advection of water from the productive shelf could be another important mechanism for the injection of labile organic matter close to the depth of the nitrite maximum. It is tempting to suggest that the degradation of this advectively transported DOC may account for a large fraction of nitrate reduction by micro-organisms. A possible scenario to explain the anomalous occurrence of maximum denitrification beneath zones of low biological production is as follows. Dense water is formed during the winter over the inner shelf, particularly the Gulf of Kutch. As this water cascades down the continental slope and finds its density level between 150 and 200 m, its oxygen content decreases rapidly due to mixing and oxidation of organic matter. Some re-oxygenation occurs close to the continental margin, contributing to lower nitrate deficits and nitrite concentrations. Ageing of this water, involving decay of the associated DOC as it moves into the ocean interior, may explain the offshore increase in the extent of denitrification. In addition, as pointed out by Naqvi *et al.* (1990), high horizontal diffusivity in the Arabian Sea could also cause a dispersal of DOC produced from the sinking particles (Karl *et al.*, 1988; Cho and Azam, 1988) away from the productive zones. This may also help in minimizing the contrasts in the chemical composition of waters beneath upwelling and non-upwelling areas.

PALEOCEANOGRAPHIC IMPLICATIONS

The above results have some significant bearings on the long-term geochemical changes in the northern Indian Ocean. If the development of reducing conditions in the Arabian Sea is facilitated by the enhanced stratification resulting from the flow of warm, fresher waters from the equatorial region during the NE monsoon, then the variability of this flow should be an important regulating factor for the intensity of denitrification on a glacial-interglacial time scale. From an analysis of $^{18}O/^{16}O$ in planktonic foraminifera in sediment cores from the Arabian Sea, Duplessy (1982) reported little east to west differences in $\delta^{18}O$ during the Last Glacial Maximum (LGM). This was in sharp contrast with the Holocene data, which showed marked zonal gradients closely reflecting the present-day salinity distribution, and was attributed by Duplessy to the weakening of the SW monsoon during the LGM. It must, however, be considered that the maintenance of a low-salinity regime in the eastern Arabian Sea is only in part due to precipitation/runoff from India. The northward flow of equatorial water (which is of the order of $10 \times 10^6\ m^3 s^{-1}$ – Shetye *et al.* 1991) during the NE monsoon is perhaps a more important mechanism, as is apparent from Wyrtki's (1971) charts showing the bi-monthly distribution of salinity at the sea surface. Consequently, the oxygen isotope data most probably reflect a weakening (if not a reversal) of the northward flow off the Indian coast during the LGM. At first glance this appears to contradict the established dominance of the NE monsoon during the LGM (Fontugne and Duplessy, 1986; and references therein), but such is not the case as will be discussed later. Reduced advection of low-salinity equatorial waters in conjunction with enhanced evaporation probably led to high surface salinities throughout the northern Arabian Sea (the LGM to Holocene $\delta^{18}O$ difference in planktonic foraminifera is close to $2^0/_{00}$ – Broecker, 1989). Given that the surface (Prell *et al.*, 1980) and intermediate depth (Kallel *et al.*, 1988) water temperatures were not very different from those observed today, a much weaker stratification should be expected to have existed in the upper layers of the glacial Arabian Sea.

Moreover, the lowering of sea level would drastically reduce the area of the continental shelves. This is expected to have resulted in a reduced formation of intermediate waters on the continental shelves during the LGM. Overall fertility and hence the subsurface oxygen demand might also be lower than they are today, due to the much weaken upwelling in the western Arabian Sea (Labracherie *et al.*, 1983).

It follows from the above discussion that a larger oxygen supply from the surface layer due to vertical mixing might combine with a smaller oxygen demand to produce a better oxygen balance at mid-depth in the glacial Arabian Sea than that which exists today. This is in conformity with the $\delta^{13}C$ record in benthic foraminifera (Kallel *et al.*, 1988).

Earlier, a glacial intensification of denitrification in the Arabian Sea had been postulated on the basis of the more intense reducing conditions observed during the

NE monsoon, and the reported dominance of NE monsoon circulation during the LGM (Naqvi *et al.*, 1990). It now appears that the latter might not necessarily imply more intense reducing conditions during peak glaciation. This is primarily due to the peculiarity of the surface circulation pattern, which probably differed greatly from that associated with the present-day NE monsoon in spite of, and indeed due to, a more intense NE monsoon during the LGM. The warm, low-salinity current in the eastern Arabian Sea during the NE monsoon is anomalous in that if flows against the wind (Shetye *et al.*, 1991). A strong wind stress can weaken such currents, and even reverse their directions (McCreary *et al.* 1986). This seems very likely to be what happened during the Last Glacial.

CONCLUSIONS

– Contrary to what is implied in previous reports, denitrification does not occur everywhere in the Arabian Sea north of an almost zonally-oriented southern boundary. Reducing conditions in the water column do not normally develop along the northern and western boundaries. The three major upwelling sites appear to be anomalously located outside the zone of intense denitrification, the axis of which extends to the southwest from the shelf edge off Gujarat. The total area of the Arabian Sea affected by denitrification is 1.37×10^6 km^2.

– The exchange of oxygen between the surface and subsurface layers through vertical mixing perhaps plays a key role in determining the extent of denitrification in the Arabian Sea, which seems to be mainly controlled by thermohaline stratification related to surface circulation. Denitrification is probably inhibited in the northwestern and western Arabian Sea due to a large downward diffusive flux of oxygen facilitated by the winter cooling of surface waters. Advection of warm, low-salinity waters from the equatorial region, however, leads to strong stratification in the eastern and central Arabian Sea during winter, inhibiting vertical mixing. Maintenance of a reducing environment in the Arabian Sea could thus be linked to this feature.

– Intense winter cooling in some shallow areas close to the coast in the northeastern Arabian Sea (especially within the Gulf of Kutch) probably leads to the formation of intermediate waters. Besides contributing to the maintenance of low salinities and low nitrate deficits close to the continental margin, and a salinity minimum at 150-200 m, this process may also inject appreciable quantities of labile DOC into the oxygen-deficient zone. Degradation of advectively transported organic matter may account for a large fraction of denitrification. This, together with the high horizontal diffusivity in the Arabian Sea (which may lead to a dispersal of DOC produced from sinking particles away from the productive zones), may account for the lack of correspondence between surface productivity and subsurface reducing conditions.

– The absence of low-salinity waters in the eastern Arabian Sea, the occurrence of high surface salinities throughout the region, and a much smaller area of the continental shelves during the glacials are expected to result in an enhanced exchange of dissolved oxygen between the surface and subsurface layers, and decreased transport of DOC to the subsurface layer through advection. These imply a relaxation of the mid-depth environment to a better oxygen balance during glacial time, in conformity with the carbon isotope record in benthic foraminifera (Kallel *et al.*, 1988).

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