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On the renewal of the denitrifying layer in the Arabian Sea

Arabian Sea
Vertical advection
Denitrification
Organic matter
Renewal time

Mer d'Oman
Advection verticale
Dénitrification
Matière organique
Temps de renouvellement

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ABSTRACT

A one-dimensional (vertical) advection-diffusion model has been applied to the deep layer characterized by a linear potential temperature (θ)-salinity relationship in the Arabian Sea to estimate the velocity of ascending motion. The results indicate that the upward velocity increases southward. Consequently, the upward flux of oxygen per unit area associated with upwelling of deep water immediately south of the denitrification zone (between latitudes 5 and 10°N) is almost twice the corresponding value for the zone of intense denitrification (between latitudes 16 and 21°N). Coupled with a southward decrease in the supply of organic carbon from the surface layer, this seems to determine the southern and lower boundaries of the denitrification zone. When normalized to phosphate, there appears to be a deficiency in nitrate, estimated as $\sim 1\,\mathrm{TgN\,a^{-1}}$, in the water upwelling at ~ 3 km within the denitrification zone, due to the downward diffusion of nitrate deficits from the denitrifying layer. Assuming that denitrification in the Arabian Sea conforms to global trends, the Liu-Kaplan model (1984) is applied to determine the renewal time of the denitrifying layer (*ca.* 150-600 m) as 1.6-3.4 a. This is consistent with some recent results supporting the view that Arabian Sea's contribution to global denitrification has been up to now severely underestimated.

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RÉSUMÉ

Renouvellement des eaux dénitrifiées de la mer d'Oman

Afin d'évaluer la vitesse du mouvement vertical ascendant dans la mer d'Oman, un modèle d'advection-diffusion à une dimension (verticale) a été appliqué à la couche profonde caractérisée par une relation linéaire entre la température potentielle et la salinité. Les résultats indiquent que la vitesse ascendante augmente vers le Sud. Il s'ensuit que le flux ascendant d'oxygène associé à la remontée d'eau profonde juste au sud de la zone de dénitrification (entre 5° et 10° N) est presque le double de la valeur correspondante dans la zone de dénitrification intense (entre 16° et 21°N). Ce résultat, et la diminution vers le Sud de l'apport de carbone organique en provenance de la couche superficielle, semblent déterminer les limites au Sud et en profondeur de la zone de dénitrification. Par rapport au phosphate, il apparaît un déficit en nitrate d'environ 1 $\mathrm{Tg.a^{-1}}$ dans la remontée d'eau à 3 000 m dans la zone de dénitrification, probablement dû à la diffusion vers le bas des déficits en nitrates à partir de la couche dénitrifiante. En supposant que dans la mer d'Oman la dénitrification suive la tendance globale, le modèle de Liu et Kaplan conduit à un temps de renouvellement de la couche dénitrifiante (150 à 600 m) de 1,6 à 3,4 ans, en accord avec quelques résultats récents selon lesquels la contribution de la mer d'Oman à la dénitrification globale aurait été jusqu'à présent très sous-estimée.

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INTRODUCTION

The modes and time scale of renewal of the oxygen-depleted, denitrifying waters found in the northern Arabian Sea are poorly understood. This introduces large uncertainties in estimates of the rate of denitrification in the Arabian Sea, since widely different values (3-30 years) of the residence time have been chosen by previous workers to calculate the rate (0.1-3.2 $\mathrm{TgN\,a^{-1}}$) from the total amount of denitrified nitrogen (Deuser *et al.*, 1978; Naqvi *et al.*, 1982). A recent work involving transports of nitrate deficits out of the denitrification zone has led to a much higher estimate ($\sim 30\ \mathrm{TgN\,a^{-1}}$), indicating possible underestimation of the Arabian Sea's contribution to global denitrification presumably arising from erroneous (high) choices of residence time (Naqvi, 1986; 1987). It now appears that the renewal of waters within the oxygen minimum layer is surprisingly rapid (Swallow, 1984). As in the oxygen-deficient environments of the eastern tropical Pacific Ocean (*cf.* Codispoti, Richards, 1976), horizontal processes appear to be the cause of most of the renewal, since the bulk ($>85\%$) of the nitrate deficit transport in the Arabian Sea is associated with lateral advection and mixing (Naqvi, 1987). However, even though the renewal of intermediate waters through horizontal processes could be rapid, the associated re-oxygenation may not be proportionately large. This is because of the low oxygen content of waters derived from the western equatorial Indian Ocean that are responsible for renewal of waters at mid-depth in the northern Arabian Sea (Swallow, 1984). In addition, the rate of deep-water upwelling in the Indian Ocean could be substantially higher than in the Pacific or in the Atlantic (Warren, 1981; Swallow, 1984), which suggests that vertical advective processes might perhaps play a more important role in supplying oxygen to the oxygen minimum layer and in determining the dimensions of the denitrifying zone. A quasi-quantitative assessment of the vertical renewal processes is presented in this report. Data on primary productivity and the nitrogen system are also examined in the light of global denitrification trends to provide additional evidence for the short renewal time and consequently high rate of denitrification within the oxygen-depleted layer.

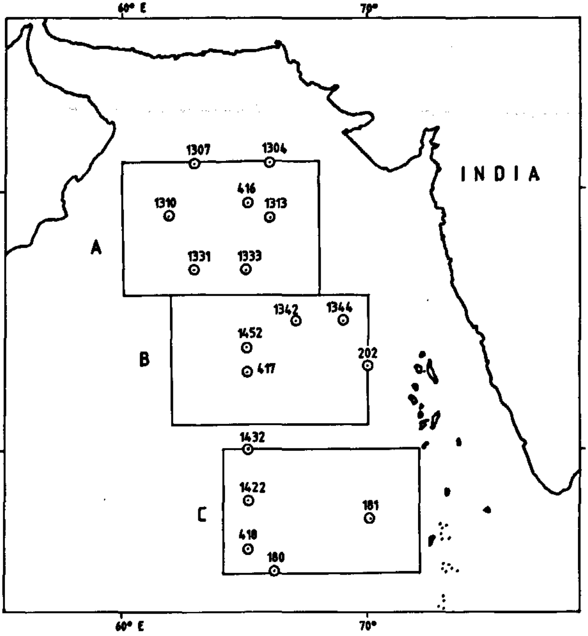

Figure 1
Chart showing station locations and subzones.

MATERIAL AND METHODS

Most of the data analyzed here were generated during some recent cruises of the research vessels *Gaveshani* and *Sagar Kanya.* Observations made at a few stations during the GEOSECS Indian Ocean programme, F.S. *Meteor*'s International Indian Ocean Expedition (IIOE) cruises (Dietrich *et al.*, 1966), and a cruise of R.V. *Atlantis II* (Deuser *et al.*, 1978) have also been examined. Station locations are shown in Figure 1; details of the sampling and analytical procedures followed on board *Gaveshani* and *Sagar Kanya* are given elsewhere (Naqvi, 1987). Potential temperature (θ) was computed from the algorithms of Fofonoff and Millard (1983). The procedure of Naqvi and Sen Gupta (1985)

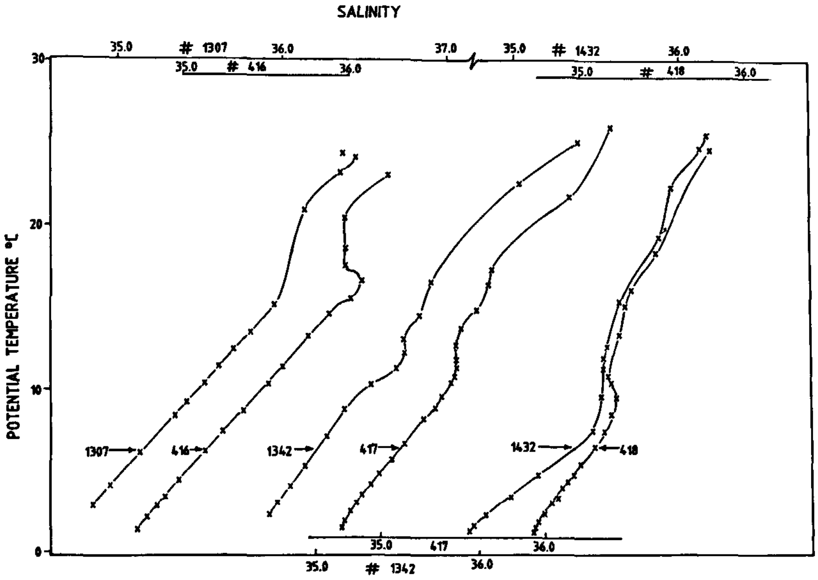

Figure 2
Potential temperature-salinity plots for stations located in subzones A (1307, 416), *B* (1342, 417), *and C* (1432, 418).

was followed for calculating the nitrate deficit (ΔN; an estimate of the combined nitrogen converted to N_2). The study area was divided into three subzones A, B and C, each having a dimension of 8° × 5° (Fig. 1). Reducing conditions are expected to prevail at mid-depth within the subzones A and B, but C is located outside the denitrification zone (*cf.* Naqvi *et al.*, 1982; Naqvi, 1986).

Weighted means of the column productivity within the three subzones were determined using all the data available at the Indian National Oceanographic Data Centre. This material comprises data obtained during the IIOE (Babenerd, Krey, 1974), and a large volume of data taken subsequently during numerous cruises of I.N.S. *Darshak*, R.V. *Gaveshani* and R.V. *Sagar Kanya*. Vertical fluxes of the particulate organic carbon at 150 m – roughly the upper boundary of the denitrifying layer – were computed from Suess' (1980) model.

Potential temperature-salinity plots were constructed individually at 6 stations, two from each of the three subzones (Fig. 2). Within the depth range of a linear θ-S relationship, average W/K was computed for A, B and C; the derivatives were obtained from the Taylor series (Craig, Weiss, 1970):

$$W/K = (\partial^2 \theta / \partial z^2)/(\partial \theta / \partial z). \qquad (1)$$

Application of a one-dimensional advection-diffusion model involves the assumption that horizontal advection is negligible within the depth range under consideration (*i.e.*, the deep layer with linear θ-S relationship). In the area of study, the thickness of this layer increases northward (Fig. 2); its upper and lower boundaries are marked in Figure 3 for each of the six stations, the data from which were used for the computation of the W/K ratio. Computed values of W/K and the model fits to the observed temperature data are also presented (Fig. 3).

In order to compute the vertical advection velocity (W), the vertical diffusion constant (K) was assumed to be constant and a value of 1.33 $cm^2 s^{-1}$ for K was selected from the literature (Munk, 1966) to estimate mean vertical velocities within the three subzones.

RESULTS AND DISCUSSION

The average velocity of ascending motion for all the three subzones (Table 1) is significantly higher than those reported from some other oceanic areas. For example, Wyrtki (1961) found W/K to vary from 1.2 to 1.8×10^{-5} cm^{-1} in four Indonesian basins and Munk (1966) reported a value of 1.16×10^{-5} cm^{-1} from the eastern Pacific, off California. Within the Arabian Sea, the rate of upwelling of deep water appears to increase southward; the upward transport of water within A (33.65×10^{11} $m^3 a^{-1}$) is almost half of the corresponding value (60.50×10^{11} $m^3 a^{-1}$) for C. Owing to marked north-south changes in properties at any given level, the differences in the upward transport of O_2 and nutrients, computed by utilizing the mean concentrations at ~3 km within the three subzones, summarized in Table 1, are even more strongly pronounced. It is obvious from these computations that the upward supply of oxygen at the 3-km level within C is more than twice the estimated transport within A. Obviously, these estimates do not necessarily apply to the lower boundary of the oxygen-deficient layer. This is because an unknown fraction of the upwelling water would contribute to the southward directed "return flow". The level at which this flow occurs is not exactly known. While Bennett (1970) and Wyrtki (1973) believe that it occurs close to the oxygen minimum, there is some evidence for its occurrence at ~3 km, the depth where a deep silicate maximum is often observed (Edmond *et al.*, 1979; Naqvi, Kureishy, 1986). The latter view is also consistent with the circulation model of Broecker *et al.* (1985). However, it would seem reasonable to assume that the relative proportions of the inputs of oxygen and nutrients to the oxygen-deficient layer as a result of upwelling of deep water will not be very different from those given in Table 1. Further, while the reoxygenation of the intermediate layer through upwelling of oxygen-rich deep water appears to increase southward in the Arabian Sea, oxygen consumption rates are expected to decrease because of a southward decrease in the downward flux of organic carbon to the denitrifying zone (Tab. 1). We

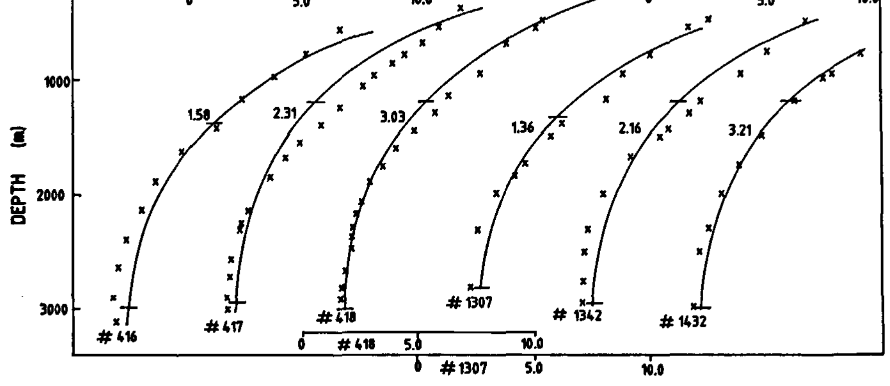

Figure 3

Model fits (solid curves) to the observed potential temperature data (crosses) for the depth intervals of linear θ-S relationships. The numbers represent the W/K (10^{-5} cm^{-1}). *The depth range of interest is marked on each profile.*

Table 1

Vertical transport estimates for the three subzones.

Subzone		Upward velocity 10^{-5} cm s^{-1}	Upward advection 10^{11} m^3 a^{-1}	NO_3-N^*	PO_4-P^*	O_2 (*)	Organic (**) flux at 150 m g m^{-2} a^{-1}	Nitrate deficit TgN a^{-1}
					Tg a^{-1}			
A	(60–68°E)	2.17	33.65	1.598	0.305	13.03	50.09	0.49
	(16–21°N)			(33.93)	(2.93)	(121)	(519)	–
B	(62–70°E)	2.90	44.95	2.353	0.354	19.84	23.84	0.07
	(11–16°N)			(37.36)	(2.54)	(138)	(247)	–
C	(64–72°E)	3.94	60.50	2.980	0.422	29.34	7.24	–
	(5–10°N)			(35.21)	(2.25)	(152)	(75)	–

(*) Numbers in parentheses give concentrations in µM dm^{-3}.
(**) Numbers in parentheses give primary production in mgC m^{-2} d^{-1}.

believe that it is the combination of these two factors, rather than a northward stagnation of intermediate layers, as believed so far (*cf.* Qasim, 1982), which is responsible for the observed southward decrease in the vertical extent and intensity of denitrification in the Arabian Sea (Fig. 4).

As stated earlier, the subzone C lies outside the denitrification zone. However, it is possible that some nitrate deficits would be advected into this region from their production zones in the northern Arabian Sea. Unfortunately, the circulation at mid-depth in the Arabian Sea is poorly understood. Quite possibly, it undergoes large seasonal changes both in magnitude and direction, in association with the monsoonal rhythm (Bennett, 1970). Thus, even though sizeable losses of nitrate deficits appear to occur as a result of lateral advection (Naqvi, 1987), it is difficult to identify the zones where the deficits are advected. Dilution through mixing probably quickly erases the characteristics of the water flowing out of the denitrification zone, since a pronounced nitrate minimum or significant nitrate deficits are not observed within C (Fig. 4). In any case, significant transports of nitrate deficits to the south are probably restricted to the upper layers. This is because a northerly flow should be expected to occur at depths greater than 3 km (Broecker *et al.*, 1985). Also, it seems reasonable to assume that the concentrations of preformed nutrients would not vary greatly within the limited area of study (*i. e.*, the ratio between "expected" nitrate and phosphate at any given level should not show significant geographical variability). With these assumptions, the computed upward nutrient transports at the 3-km level within the subzone C have been utilized for normalizing estimates for the other two subzones. Normalizing to phosphate, there appears to be a deficit in nitrate of about 0.49 and 0.07 TgNa^{-1} within A and B, respectively. When the total deficit is normalized to the area of the denitrification zone (1.95×10^6 km^2; Naqvi, 1986), the overall deficit in nitrate associated with the water upwelling at the 3-km level comes close to 1 TgNa^{-1}. This compares favourably with Naqvi's (1987) estimate for the net losses of nitrate deficits through the lower boundary (1.5 TgNa^{-1}).

By using the available data from various marine denitrification sites, some model constraints can be applied to determine the ventilation time of the denitrifying layer in the Arabian Sea. Liu and Kaplan (1984) found a direct correspondence between the fluxes of carbon consumed during denitrification and the organic carbon available as macroparticles within the denitrifying layer, both normalized to the surface productivity. The data point representing the Arabian Sea, based on the results of Deuser *et al.* (1978), was, however, anomalous in that the ratio between the percentage of available organic carbon to the normalized flux of carbon consumed during denitrification was unreasonably high (32.5) in comparison with the rather narrow range (1.8-4) deduced for the other zones. As pointed out by Liu and Kaplan, this departure from the global trend could result from an underestimation of the extent of denitrification in the Arabian Sea.

Utilizing data from several stations listed in Table 2, we computed the integrated nitrate deficit and nitrite concentrations within the denitrifying layer (*ca.* 150-600 m) taken as the depth zone where the secondary nitrite was observed. Following the procedure of Liu and Kaplan (1984), the percentage of primary product-

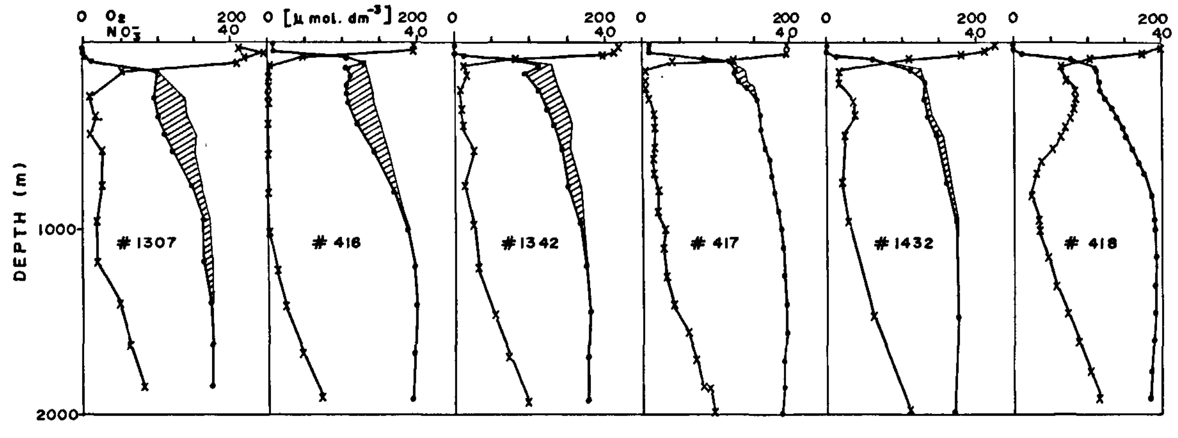

Figure 4

Profiles of nitrate (circles) and dissolved oxygen (crosses). The hatched area gives the amount of denitrified nitrogen.

Table 2

Fluxes of the organic carbon consumed during nitrate reduction and the fraction of surface primary production available as macroparticles within the denitrifying layer at selected stations in the Northeastern Arabian Sea.

Station No.	Latitude/longitude	U (m)	L (m)	X ($g-at\ m^{-2}$)	Y ($g-at\ m^{-2}$)	$\Delta f/P$ (%)	$\tau.\varphi_c$ ($g-at\ m^{-2}$)
AN 2342	20°35'N 68°06'E	195	670	2.828	0.797	14.41	3.933
AN 2353	20°34'N 68°06'E	195	670	2.683	0.772	14.41	3.740
ME 222	19°38'N 66°25'E	145	650	7.455	0.508	20.91	9.573
ME 224	20°20'N 67°09'E	200	630	2.692	0.512	13.53	3.621
GA3722	20°00'N 66°37'E	140	600	2.934	0.764	21.31	4.049
GA 2702	20°00'N 66°48'E	140	600	3.054	0.934	21.31	4.284
GEOSECS 416	19°48'N 64°37'E	140	550	2.499	0.770	20.69	3.509

U = Upper boundary of denitrification.
L = Lower boundary of denitrification.
X, Y = Integrated value of nitrate deficit and nitrite, respectively.
$\Delta f/P$ = Percentage of surface primary production available within the denitrifying layer as macroparticles.
φ_c = Annual fluxes of carbon consumed during nitrate reduction.
τ = Average renewal time of the denitrifying layer.

ion available as organic macroparticles ($\Delta f/P$) within this depth interval was computed from the equation of Suess (1980):

$$\Delta f/P = 4200[(Z_1+8.91)^{-1}-(Z_2+8.91)^{-1}], \tag{2}$$

where Z_1 and Z_2 are the depths in metres representing the upper and lower boundaries of denitrification layer, respectively.

The extent of carbon consumed during denitrification was estimated from the equation:

$$\tau.\varphi_c = 1.25X + 0.5Y, \tag{3}$$

where φ_c is the annual rate of organic carbon consumed during nitrate reduction, τ is the residence time of water within the denitrifying layer (the product of the two gives the extent of carbon consumed at any given time), and X and Y are the integrated values of nitrate deficit and nitrite, respectively. The factors 1.25 and 0.5 take into account the electrons involved in the reduction of NO_3^- to N_2 and NO_3^- to NO_2^-, respectively. The results of the above computations are also summarized in Table 2.

If we assume that denitrification in the Arabian Sea conforms to the global trend (*i.e.*, the ratio between $\Delta f/P$ and φ_c/P should lie between 1.8 and 4, as in the other denitrification sites), and utilize Qasim's (1982) annual average primary productivity north of latitude 15°N (305 $gC\,m^{-2}\,a^{-1}$), the average renewal time could be deduced to lie between 1.6 and 3.4 a. The upper limit agrees well with the lower limit of the residence time of the Persian Gulf core layer (3 a) derived by Deuser *et al.* (1978). Also consistent with Naqvi's (1986; 1987) estimate ($\sim$4a), the upper limit appears to be more reasonable since it corresponds to $(\Delta f/P)/(\varphi_c/P) = 4$, the value observed in the ETNP, an area similar to the Arabian Sea in regard to physical dimensions of the denitrifying layer, concentrations of O_2, NO_2^- and NO_3^- and the amounts of denitrified nitrogen (Naqvi *et al.*, 1982; Naqvi, 1986). Even allowing room for the uncertainties inherent in such calculations, it is clear that the renewal time of the denitrifying layer is surprisingly low. Since estimates of the total amount of denitrified nitrogen ($\sim$100 Tg) suffer from little uncertainty (Naqvi, 1987), the high renewal times selected by the previous workers have probably resulted in a severe underestimation of the rate of denitrification in the Arabian Sea.

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