

INORGANIC COMBINED NITROGEN BUDGET OF THE ARABIAN SEA: SOME GEOCHEMICAL AND CLIMATIC IMPLICATIONS

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ABSTRACT

Estimates of the local sources and sinks of inorganic combined nitrogen in the Arabian Sea suggest a net loss of $\sim 3 \times 10^{13}$ gN y^{-1} . This seems to be made up largely by the upward flux facilitated by a high rate of upwelling of the inflowing bottom water. It is proposed that the changes in the deep-water upwelling rate in response to temporal variability of the monsoons and to fluctuations in the oceanic thermohaline "conveyor" may regulate the upper and intermediate depth chemical composition and the productivity of the surface waters in the North Indian Ocean. A lower rate of deep water upwelling is expected to have resulted in an intensification of the Indian Outflow during the latest glacial maximum causing a depletion of nutrients in the upper/intermediate layers and their relative enrichment in deep waters. Such a change in the deep oceanic circulation associated with the fluctuations in deep water upwelling can explain the benthic foraminiferal carbon isotopic and cadmium data and has implications vis-a-vis the glacial-interglacial atmospheric CO₂ oscillations.

INTRODUCTION

The North Indian Ocean is characterized by a very pronounced deficiency of dissolved oxygen in the upper/intermediate water column (Wyrтки, 1971) leading to reducing conditions in the Arabian Sea (Naqvi, 1987). Some recent studies have revealed that the locus of the most

severe oxygen depletion probably underwent significant vertical migrations associated with the climatic cycles (Kallel et al., 1988; Chen and Prell, 1990). These authors have shown from measurements of $^{13}\text{C}/^{12}\text{C}$ in benthic foraminifera that there probably existed a sharp discontinuity in the thermohaline structure in the North Indian Ocean at ~2 km depth during the last glacial maximum (LGM). Above this level, the waters were probably more oxygenated (higher $\delta^{13}\text{C}$) during the LGM as compared to today; the deeper waters, on the other hand, were more oxygen-depleted (LGM $\delta^{13}\text{C}$ as low as -1‰) particularly in the Bay of Bengal. Measurements of Cd/Ca in benthic foraminifera are generally consistent with these findings (E.A. Boyle, personal communication).

What caused the glacial-interglacial changes in the vertical hydrochemical structure is not known. Kallel et al. (1988) suggested that the glacial intermediate waters were better ventilated. They considered three possible sources of intermediate waters that could have brought about better ventilation of the upper/intermediate layers: formation of highly saline waters in the Arabian sea; an increased flow of intermediate waters from the Pacific through the Indonesian seas; and a greater northward penetration of the Antarctic Intermediate Water. Chen and Prell (1990) proposed that the deep waters characterized by low $\delta^{13}\text{C}$ were locally formed. However, considering that the glacial sea surface temperatures were not very different from those observed today (CLIMAP, 1981), and that the area of the continental shelves (where dense waters could be formed) was much smaller, it is very unlikely that a significant local production of intermediate/deep waters could have occurred in the North Indian Ocean during the LGM. Increased flow from the Pacific, favoured by Kallel et al. is also improbable because this flow presently occurs to compensate for the advection of the North Atlantic "Deep

Water (NADW) into the Pacific (Gordon, 1986). With the production of the latter greatly reduced during the last glaciation (Streeter and Shackleton, 1979; Duplessy *et al.*, 1988), the intrusion of low-salinity intermediate waters from the Pacific to the Indian Ocean should actually have been smaller. Increased input from the Southern Ocean could also be ruled out in view of the evidence for a large decrease in surface water $\delta^{13}\text{C}$ in the Southern Ocean during the LGM (Labeyrie *et al.*, 1987; Charles and Fairbanks, 1990). In this communication, I shall propose that the deep hydrographic front in the glacial North Indian Ocean could arise from a decrease in the deep water upwelling rate. If so, then it may have important implications on the paleoproductivity of the region, oceanic nitrogen inventory as well as the glacial-interglacial atmospheric CO_2 changes.

THE NITROGEN BUDGET

In order to identify the processes which might have caused the glacial-interglacial variation in the vertical distribution pattern of oxygen and nutrients in the North Indian Ocean it is necessary to understand those which determine the vertical profiles of these properties today. As shown below, useful insight into these processes could be gained by examining the current balance between the losses and supply of inorganic combined nitrogen in the Arabian sea.

Estimated strengths of various local sources and sinks of inorganic combined nitrogen in the Arabian Sea are presented in Table 1. This budget differs from the one proposed recently by Somasundar *et al.* (1990) in several respects. First, it takes into account inputs from the atmosphere, and losses through sedimentary denitrification and as N_2O (to the atmosphere and within the reducing zones), not considered by Somasundar *et al.* Second, it does

not consider any change due to biological production; the organic matter exported out of the euphotic zone is assumed to undergo decomposition within the Arabian Sea itself. Third, and more important, the loss due to denitrification (atmospheric flux = 2.05 Tg N y^{-1}) considered by Somasundar *et al.* was much lower than the value (30 Tg N y^{-1}) chosen here. Consequently, unlike the budget of Somasundar *et al.*, which implies that the Arabian Sea acts as a net source of inorganic combined nitrogen, the present work indicates that it is a net sink of substantial magnitude ($\sim 30 \text{ Tg N y}^{-1}$). This, of course, is to be expected since the Arabian Sea houses one of the three major oceanic denitrification sites. It may be noted here that one of the terms in Table 1 subject to greatest uncertainty is the sedimentary denitrification. In order to estimate this term, I have used the mean sedimentary denitrification rate determined off the Washington coast (Christensen *et al.*, 1987). In view of recent results obtained by Devol (1991), it is very probable that the sedimentary denitrification is underestimated in Table 1. Therefore, the overall strength of the Arabian Sea sink may be higher than estimated here.

The nitrogen required for the mass balance should be supplied through advection and diffusion from the south. Using the estimates by Metzl *et al.* (1990) of the advective flows into and out of the Arabian Sea, for 5 layers deeper than 400 m, together with the estimated average nitrate concentrations (Table 2), the net advective transport of nitrate below 400 m was computed as $\sim 114 \text{ Tg N y}^{-1}$. Most of it seems to occur through the flow of the bottom water. It may be pointed out, however, that the estimate of the transport into the Arabian Sea below 4 km (8 Sv - Table 2) may be unrealistically high as it is twice the estimated bottom water transport into the Somali Basin through the Amirante Passage (Barton and Hill, 1989). How much of this flow reaches the Arabian Basin is not known. However, even

allowing room for the uncertainties inherent in the calculations involved, it is obvious that the large nitrogen deficiency in the upper layers could be made up mostly by inputs from the bottom layer.

POTENTIAL ROLE OF THE VIGOROUS DEEP-WATER UPWELLING

The high rate of transfer of nutrients from the deep waters to the upper/intermediate layer is probably facilitated by a high rate of upwelling of deep waters in the North Indian Ocean (Warren, 1981; Swallow, 1984; Somasundar and Naqvi, 1988; Barton and Hill, 1989). I suggest that this may be principally responsible for maintaining high nutrient concentrations within the thermocline of the North Indian Ocean, rather than the vigorous vertical mixing in the Indonesian seas, as proposed by Gordon (1986). Ironically, the large upward flux of nutrients may not only compensate for the nitrate losses due to denitrification within the upper layers, but it may also be responsible, on long time scales, for creating the conditions required for the onset of denitrification: The high nutrient concentrations within the thermocline result in elevated primary productivity of the surface waters which in turn leads to increased oxygen demand at mid-depth. The acute oxygen depletion in the upper/intermediate layers could, therefore, be a direct consequence of the high rate of deep-water upwelling.

The deep-water upwelling in the North Indian Ocean could be paced by a combination of regional and global processes. It may be controlled regionally by the monsoonal wind-driven coastal upwelling off Arabia and Somalia. This may be augmented by the production of the NADW since the upwelling of deep waters in the Pacific and Indian Oceans is necessary to drive the NADW production as a part of the overall global "conveyor" system (Gordon, 1986; Broecker and Denton, 1990). During the last glacial maximum (LGM),

however, when the coastal upwelling in the Arabian Sea was probably much weaker (Duplessy, 1982), and there was suppressed formation of the NADW (Streeter and Shackleton, 1979; Duplessy *et al.*, 1988), the upward movement of deep waters in the Indian Ocean is expected to have been much slower. This would have two important implications:

First, a smaller upward flux of nutrients would lower the nutrient concentrations within the thermocline, causing a decrease in the overall fertility of the Arabian Sea. This is supported by the sedimentary record [lower carbonate content of the glacial sediments often attributed to terrigenous dilution (see, for example, Prell and Curry, 1981)]. A lower export production in turn would translate into reduced nutrient regeneration at mid-depth and consequently a better oxygen balance. This is consistent with the carbon isotopic data on benthic foraminifera (Kallel *et al.*, 1988; Chen and Prell, 1990). A less intense "nutrient trap" (lower productivity both causing and resulting from the lower intermediate depth nutrient contents) could thus explain the heavier carbon in the glacial foraminifera without calling for an enhanced ventilation of the intermediate waters. Such a scenario is, of course, inconsistent with the models that invoke and expansion of the oceanic oxygen-deficient environments towards the end of glacial periods for modulating the climatic cycles (McElroy, 1983; Knox and McElroy, 1984).

Second, a less vigorous upward advection could also alter the deep circulation drastically. It is very likely that as the rate of deep water upwelling decreased, a significantly larger fraction of the bottom water moving northward returned at depth to the circumpolar region. This could produce the deep hydrographical front reported by Kallel *et al.* It may be noted that the return flow (outflow) probably occurs even today (at ~ 3 km depth)

(Broecker *et al.*, 1985), although it seems to be rather weak as inferred from the tracer distributions (Edmond *et al.*; Warren, 1981; Swallow and Pollard, 1988). Significantly, there appears to be some observational support for changes in the southerly flow at these depths associated with the monsoonal variability: Warren and Johnson (1990) report an absence of a deep reversal off the Somali coast during the anomalously weak southwest (SW) monsoon of 1987. Their observations (southwestward deep flow throughout the year) are at variance with those of Schott *et al.* (1989) which suggested a seasonal reversal with a flow toward northeast during the SW monsoon and toward southwest during the northeast (NE) monsoon. Warren and Johnson propose that the usual southwestward flow may be fed by the widespread upwelling of bottom water, and that it may be reversed under a moderate or intense SW monsoon. It would, therefore, be reasonable to assume that the deep outflow would exhibit large variability on a glacial to interglacial time scale, and it might have intensified greatly during the last glacial maximum when the NE monsoon was predominant (Duplessy, 1982).

If the deep circulation loop did indeed intensify during the LGM, then the nutrient-rich Indian Outflow Water might have been a much more important source for the Antarctic Bottom Water (AABW) formation as the contribution from the NADW was greatly reduced. Indeed since the deep water upwelling is expected to have been suppressed in the Pacific as well in response to a cessation of the NADW formation, a similar change in the deep circulation may also be expected to occur in the Pacific. The ensuing increase in the residence time of the deep water is supported by the data on the ¹⁴C age difference of the benthic and planktonic foraminifera (Shackleton *et al.*, 1988). Increased inputs from the nutrient-rich deep Indian and Pacific outflows as compared to the nutrient-poor NADW

may explain the low $\delta^{13}\text{C}$ in the Southern Ocean during the LGM (Curry *et al.*, 1988; Charles, 1991). As a very important consequence of these changes in the deep-sea circulation pattern, there would have occurred a net transfer of nutrients and CO_2 from the intermediate to deep layers as suggested by the sedimentary record. As shown by Boyle (1988 a,b) this has important implications on the atmospheric CO_2 and hence the climate.

The above discussion assumes that a continuity of flow existed between the North Indian Ocean and the Southern Ocean during the LGM as it does today and that the deep circulation loop intensified in response to a decreased rate of deep-water upwelling. This requires the deep waters in the equatorial Indian Ocean to be similar to those in the north and the south. However, the benthic foraminiferal isotopic records from the equatorial region indicate lower $\delta^{18}\text{O}$ and higher $\delta^{13}\text{C}$ as compared to the North Indian Ocean, prompting Chen and Prell (1990) to suggest that the nutrient-rich deep waters in the North Indian Ocean were locally produced. However, as stated earlier, the glacial surface temperature in the North Indian Ocean were probably not low enough to result in the deep water formation. I believe that the observed higher $\delta^{13}\text{C}$ in the glacial foraminifera of the deep equatorial Indian Ocean is an artifact produced by very low sedimentation rates and, therefore, does not negate the conclusions reached here.

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Table 1: Local sources and sinks of inorganic combined nitrogen in the Arabian Sea.

SOURCE/SINK	STRENGTH (Tg N y ⁻¹)	REFERENCE
<u>SOURCES</u>		
River runoff	0.1	Somasundar <i>et al</i> (1990)
Red Sea	0.8	Naqvi <i>et al</i> (1986); Bethoux (1988)
Persian Gulf	0.3	This study [*]
Nitrogen fixation	1.5	Somasundar <i>et al</i> (1990)
Atmospheric input	0.7	This study ^{**}
TOTAL	3.4	
<u>SINKS</u>		
Water column denitrification	30.0	Naqvi (1987); Naqvi and Shailaja (1992)
Sedimentary denitrification	1.0	This study ^{**}
N ₂ O loss to the atmosphere	0.3	Law and Owens (1990); Naqvi and Noronha (1991)
N ₂ O loss within the reducing zones	2.2	Naqvi and Noronha (1991)
Burial	0.2	Somasundar <i>et al</i> (1990)
TOTAL	33.7	

* Assuming similar "excess" nitrogen concentrations in the Red Sea and Persian Gulf outflows.

** Utilizing global estimate (Codispoti and Christensen, 1985) and the area of the Arabian Sea.

*** Using the estimate of Christensen *et al.* (1987) for the shelf sediments off Washington (0.57 pmol. cm⁻² s⁻¹).

Table 2: Advective transports of nitrate into (+) and out (-) of the Arabian Sea below 400 m.

LAYER	WATER TRANSPORT* (Sv)	MEAN NO ₃ CONC.** (μ M)	NO ₃ FLUX (Tg N y ⁻¹)
400 m - σ_{θ} =27.1	- 0.3	27.9	-3.7
σ_{θ} = 27.1-27.4	- 0.9	31.4	-12.5
σ_{θ} = 27.4-27.65	+ 0.6	37.8	+10.0
σ_{θ} = 27.65-4,000m	- 0.3	37.6	- 5.0
4,000m - Bottom	+ 8.0	35.5	+125.3
TOTAL (400 m-Bottom)			+114.1

* Metzl et al. (1990)

** Estimated from the available data for the respective boxes.