CHAPTER 7

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The western continental margin of India offers intriguing conditions for oceanographers to explore. Located in the monsoon region, surface currents along the Indian west coast, like elsewhere in the North Indian Ocean, are reversed completely every six months: the West India Coastal Current (WICC) flows equatorward during the Southwest Monsoon (SWM) and poleward during the Northeast Monsoon (NEM). However, these currents are not forced by local winds alone. Instead, circulation in the region, forms a component of the large-scale circulation in the entire North Indian Ocean, and is, to a large extent, remotely forced.

Seasonal changes in hydrography and circulation along the west coast of India bring about large variations in biogeochemical cycling. However, biogeochemical processes over this shelf had not been studied systematically and in detail so far. The present study provides the first comprehensive set of data on several physical, chemical and biological variables based on observations made on more than twenty cruises covering the entire shelf. Most of these cruises were undertaken after 1995 and included observations along fixed cross-shelf sections. In addition, a short (~10 km), shallow (depth < 30 m) section consisting of five stations off Candolim (Goa) has been occupied frequently since 1997 to investigate temporal changes in the coastal biogeochemical environment. Major results of the investigation are given below.
7.1 Major Findings

7.1.1 Pelagic Processes over the Western Indian Continental Shelf

- In conformity with previous reports, upwelling has been found to occur along the entire coast with a gradual progression from the south to the north. While the data generated in the present study show that upwelling goes on from June to December, earlier reports indicated that the process begins in the south in February/March (observations were not made in the present study during February-June in the southern region). This implies that the length of the upwelling period far exceeds that of the SWM, underscoring the role of remote processes in forcing upwelling along this coast. There are two aspects of upwelling in this region that distinguish it from the same process off the Somali and Arabian coasts: (1) Upwelling velocities are probably much lower off India; and (2) The cold upwelled water is generally prevented from reaching the surface by a thin (~10 m) warm, low-salinity layer that is formed due to intense precipitation and land runoff, and maintains strong near-surface thermohaline stratification. These peculiarities entail a more effective utilization of upwelled nutrients locally and a more severe O₂ depletion in subsurface waters over the Indian shelf.

- Beneath the equatorward surface flow there exists a poleward undercurrent that brings fresher and relatively oxygenated water from the south to the eastern Arabian Sea just off the continental slope. Although this undercurrent is a component of the SWM circulation, its signatures have been noticed on occasions during the NEM as well, implying
considerable interannual variability. The water upwelling along the Indian coast, derived from the region affected by the undercurrent, is initially O₂-poor but not suboxic (O₂ > 25 μM). However, over the continental shelf it loses the small quantities of dissolved O₂ due to respiration both with time and distance inshore such that at its peak the hypoxic (O₂ < 22 μM) zone includes the entire shelf. The area of this natural hypoxic zone (~180,000 km²) is an order of magnitude greater than the area of the largest human-induced hypoxic zone in the Gulf of Mexico.

- The upwelled water is initially rich in nutrients (NO₃⁻ > 20 μM), and once it gets close to the euphotic zone it stimulates rich plankton growth. Due to the strong near-surface stratification, maximal primary production often occurs a few metres below the surface. Column production in the region (up to 6 g C m⁻² d⁻¹) has been found to be among the highest observed anywhere in the Arabian Sea. The eventual decay of organic matter completely strips the sub-pycnocline waters of dissolved O₂ over large parts of the inner- and mid-shelf, triggering extensive denitrification. This process begins in July off Mangalore, in August off Goa and in September off Mumbai. South of about 12°N latitude, O₂ concentrations over the shelf do not generally fall to suboxic levels (<1 μM). Within about a month of the onset of denitrification, all oxidized nitrogen forms are lost over the inner- and sometimes the mid-shelf regions resulting in sulphate reduction in near-bottom waters. Anoxic conditions may last up to November/December in the north (off Mumbai), but are probably terminated earlier (September/October) in the south (off Mangalore).
follows the reversal of surface current and the establishment of the NE Monsoon circulation: the poleward WICC causes downwelling over the Indian shelf and the water column becomes well oxygenated. Relatively oligotrophic conditions prevail during the NE Monsoon and Spring Intermonsoon seasons.

- Quasi-time-series observations along the shallow Candolim section have facilitated the construction of monthly climatologies of various physical and chemical variables. The results provide for the first time records of changes in these parameters over one complete annual cycle including the evolution of O₂-deficiency in shallow waters, in response to the monsoonal forcing. The seasonal changes displayed by the climatology are similar to those observed during numerous repeat samplings along longer cross-shelf Goa transect, but appreciable interannual changes in the timing and spatial patterns of suboxic and anoxic conditions have been recorded.

- Repeat observations at same sites have been used to arrive at an order-of-magnitude estimate of pelagic denitrification rate - 0.8 µmole NO₃⁻ l⁻¹ d⁻¹, on an average. The total rate over the shelf has been estimated to be 1.3-3.8 Tg N y⁻¹. This corresponds to 4-12% of the denitrification rate for the perennial suboxic zone of the open Arabian Sea.

- H₂S was detected in concentrations reaching up to 21 µM off Goa, 15 µM off Mangalore and 20 µM off Mumbai. Such high levels of H₂S, seldom seem in open coastal waters, were never reported previously from the Arabian Sea and probably reflect an intensification of the shallow O₂-
deficient system through enhanced anthropogenic nitrogen loading in recent years.

- As expected NH$_4^+$ is found to accumulate in high concentrations (up to 21 μM) in the sulphide bearing waters. Its upward diffusion seems to sustain moderate primary production in the thin oxygenated layer overlying anoxic waters. In contrast, primary productivity rate in the O$_2$-depleted waters is very low even when these waters are found well within the euphotic zone.

- An unexpected feature of the nitrogen cycling was an unprecedented accumulation of N$_2$O – the highest concentration observed (765 nM) being over 4 times the highest value previously reported from the ocean. Association of the high N$_2$O concentrations with very high NO$_2^-$ (up to 16 μM) suggests production through denitrification; this is supported by laboratory experiments involving incubation of water samples. Transient build up of N$_2$O probably occurs due to the low N$_2$O reductase activity in shallow, rapidly denitrifying waters that are subjected to frequent aeration through turbulence. This sustains a high rate of emission of N$_2$O to the atmosphere (up to 0.38 Tg N$_2$O y$^{-1}$). These observations imply that a very substantial fraction of NO$_3^-$ undergoing denitrification may end up as N$_2$O.

- Inter-relationships between the dissolved inorganic nitrogen (DIN = NO$_3^-$ + NO$_2^-$ + NH$_4^+$), dissolved inorganic phosphorus (DIP) and H$_2$S reveal that while the atomic DIN/DIP ratios maintained during decay of organic matter using O$_2$ and NO$_3^-$ as the oxidants are only slightly lower than the theoretical (Redfield) values, the expected ratio is not maintained during sulphate reduction. That is, there exists much more DIP in the sulphide bearing waters than the amount expected from the DIN concentration. This
is attributed to the mobilization of phosphate from sediments under anoxic conditions through dissolution of the iron-oxyhydroxo-phosphates (FeOP) complex. The same process also seems to lower the H$_2$S/DIP ratio. The observed H$_2$S/NH$_4^+$ ratio is slightly higher than the theoretical value, but the scatter is large and the departure might result from the diffusion of NH$_4^+$ from sediments to the overlying bottom waters.

- Isotopic composition of NO$_3^-$ in shallow suboxic waters shows much smaller enrichment of heavier isotope ($^{15}$N) associated with denitrification than observed in the open ocean denitrifying zones. The results indicate a lower isotopic fractionation factor in the shallow suboxic zone (7.4°/oo as compared to 25°/oo in the open ocean). Alternatively, denitrification in sediments and mixing between anoxic and oxic waters might also pull down the $\delta^{15}$N values of NO$_3^-$ in the area of study.

### 7.1.2 Sedimentary Nitrogen Cycling

- The continental shelf sediments examined are found to serve as a sink for combined nitrogen. With the exception of two cores, N$_2$O concentrations at the sediment surface were higher (21-466 nM), indicating that the sediments serve as a source of N$_2$O to the overlying water column. A net consumption of N$_2$O has been found to occur deeper in the sedimentary column (a few centimeters below the sediment-water interface).

- Sedimentary denitrification rate measured with the acetylene block technique range between 0.17 and 1.45 pmol NO$_3^-$ cm$^{-2}$ s$^{-1}$ with the maximum observed in the mid-shelf region. The rates are on the lower side of the range reported from other continental margin sediments. When
extrapolated to the total area of continental shelves in the Arabian Sea (0.51 x 10^{12} \text{ m}^2) the total sedimentary denitrification rate works out to be 0.38-3.5 (average 1.33) Tg N y^{-1}, which is of the same order of magnitude as the pelagic denitrification rate over the Indian shelf. Thus, while benthic denitrification over the Arabian Sea continental shelves has the potential to counter inputs of combined nitrogen due to human activities, the fact that a substantial fraction of nitrogen is reduced to N_2O means that this process is of little environmental benefit.

- Significant changes have been observed in the concentrations of nutrients and dissolved gases in bottom waters enclosed by benthic chambers deployed over periods of ~24 hours. While the dissolved O_2 levels decreased with time, those of pCO_2 and N_2O showed the opposite trend. These results imply that the respiratory processes within the sediments result in the supply of significant quantities of nutrients and gases to overlying waters sustaining biological production and emission of radiatively important gases to the atmosphere.

- Porewater NO_3^- profiles have been simulated with a simple one-dimensional reaction-diffusion model. The three cores selected for simulation represented different environments and came from depths ranging from 29 to 300 m. Still values of the first order denitrification rate constant (k_d) do not show much variability (1.4 x 10^{-5} to 2.54 x 10^{-5} \text{ s}^{-1}). Estimates of NO_3^- diffusivity (D) corresponding to best fits of simulated profiles to observations are more variable (3.2 x 10^{-5} to 10.1 x 10^{-5} \text{ cm}^2 \text{ s}^{-1}). The diffusivity was the highest for the core having the highest bottom water O_2 concentration that presumably favoured macrobenthic activity.
The present estimates for D are in good agreement with the literature values suggesting that the measured denitrification are perhaps of the right magnitude.

7.2 Recommendations for Future Research

- The results of the present study suggest that the coastal zone along India is being adversely impacted by anthropogenic activities that have potential not only to affect local living resources but also to provide positive feedback to global warming through enhanced emissions of greenhouse gases, particularly N₂O. A long term programme to monitor the physico-chemical environmental changes and assess their impact on ecosystems must be initiated. Such a multi-disciplinary programme should have both observational and modeling components. Its should aim at reaching an understanding of the budgets and interactive transformations of the major biogenic elements (carbon, nitrogen, phosphorus, silicon and sulphur) over the continental margin of India and their links with open-ocean biogeochemical processes, ultimately leading to system models capable of predicting the impacts of climate shifts on the global scale as well as of local/regional environmental changes on our coastal seas.

- There is very little quantitative information presently on the fluxes of nutrients from the land to coastal seas through atmosphere and rivers from South Asia, a region that accounts for roughly one-fifth of the total global consumption of nitrogenous fertilizers. As the results of the present study clearly show, the coastal oceanic environment in the region is extremely variable and hypersensitive to minor changes in the nutrient supply.
Therefore, the anthropogenic inputs of nutrients to our coastal seas need to be adequately quantified in order to control to the maximum possible extent the overfertilization of coastal waters and to mitigate its adverse effects.

- In order to refine estimates of sedimentary denitrification, more measurements are required covering a wider depth range and with better seasonal coverage. Direct measurements of N$_2$ flux to the overlying waters should be made through deployments of benthic landers. These should be supplemented with incubation experiments involving isotope-pairing.

- Large departures of the observed relationships between DIN, DIP and H$_2$S expected from the Redfield-Ketchum-Richards (RKR) model seem to suggest adsorption/desorption of phosphorus on sediments exposed to different redox conditions. There is also a possibility that redox cycles of nitrogen and trace metals may be to some extent coupled in the investigated area. Detailed investigations on these aspects fell outside the scope of the present study, but should be taken up in future.

- The Arabian Sea has long been recognized as a region of significant N-fixation, mostly through blooms of *Trichodesmium* during the late NEM and SI. However, such blooms, extensively observed previously (Devassy et al., 1978), were not sighted in the coastal zone during any of the cruises/field trips undertaken as a part of this study. It is possible that a decrease in the abundance of *Trichodesmium* has occurred recently in response to elevated combined nitrogen levels in surface waters due to anthropogenic loading. Measurements of N-fixation, although planned initially, were not made due to the absence of *Trichodesmium*, but a
detailed study dealing with the impact of eutrophication on N-fixation is required for a more complete understanding of nitrogen cycling in this part of the ocean that has few analogues elsewhere.