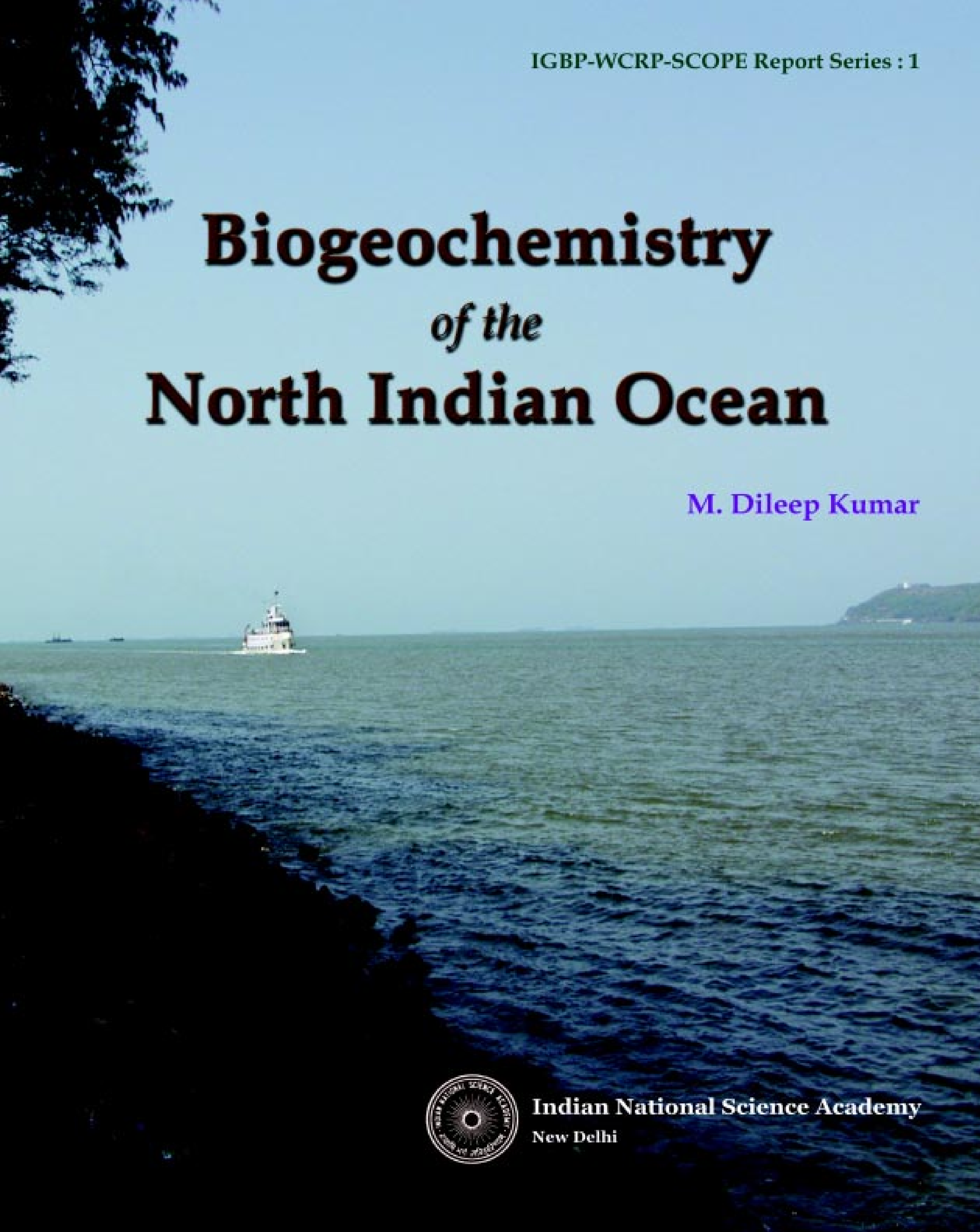

IGBP-WCRP-SCOPE Report Series : 1

Biogeochemistry *of the* North Indian Ocean

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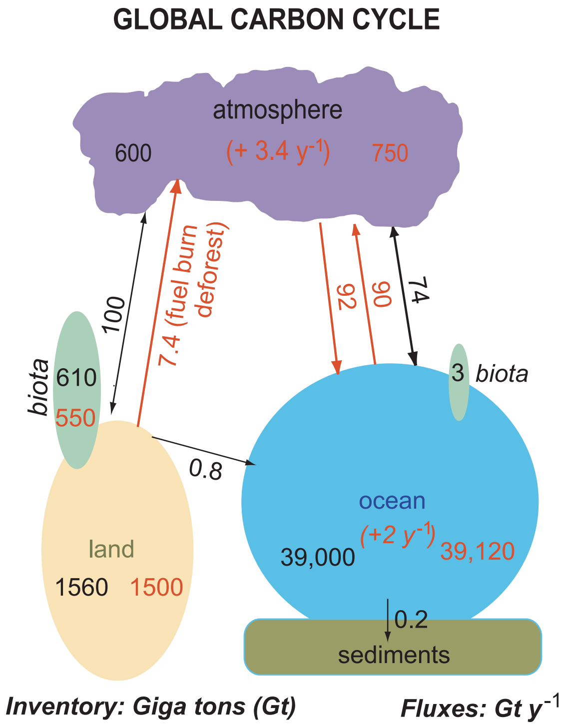

Figure 1. Global Carbon budget (after Siegenthaler and Sarmiento, 1993). Numbers in black are preindustrial and red are those influenced by human activities. Numbers inside the earth compartments are the respective reservoir sizes and those next to arrows are rates of carbon transfer. Black arrows indicate estimated rates for preindustrial era whereas red arrows account for anthropogenically modified rates. Red numbers within brackets are the accumulation rates of anthropogenic carbon dioxide in atmosphere and oceans in Gt y^{-1} (Gt C = 10^{15} g C). The missing carbon of 2 Gt y^{-1} is that anthropogenic component for which the sink is expected in temperate coniferous forests.

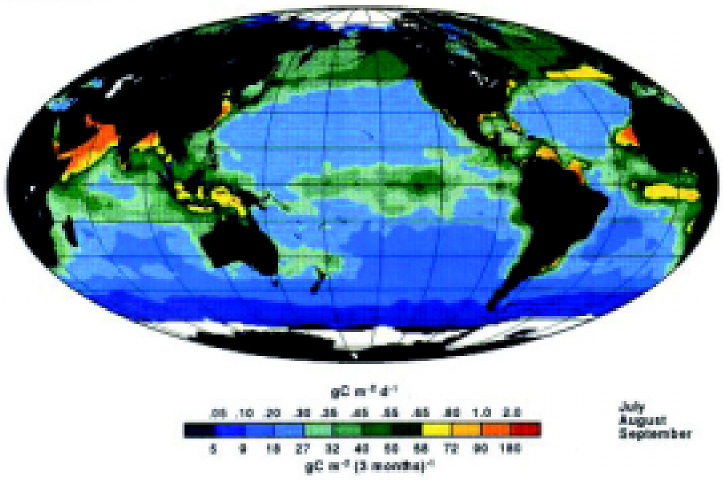

Figure 10. Satellite derived imagery of primary production in the world oceans during summer (from Behrenfeld and Falkowski, 1997). The North Indian Ocean is one of the most productive regions in the world where the Arabian Sea fixes more carbon than the Bay of Bengal. Regional trends observed in the adjacent picture are more or less the same in all seasons but with changes in magnitudes.

Biogeochemistry of the North Indian Ocean

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October 2006

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Foreword

Preface

ACKNOWLEDGEMENTS

The author is grateful to Prof. J.S. Singh, Chairman, IGBP-WCRP-SCOPE Committee of INSA and Dr. S.R. Shetye for inviting this contribution. This attempt is greatly benefited and encouraged by comments from Drs. D. Shankar, Y. Sadhuram, P.V. Narvekar, A.C. Anil, S. Prasannakumar, N. Ramaiah, T. Pankajakshan, V.V.S.S. Sarma and Prof. N.S. Sarma. This booklet could not have been what it is without the help from Dr. P.V. Bhaskar, Shri S.P. Sharma, Shri Arun Mahale and Mrs Sujal Bandodkar. This is NIO contribution number 4152.

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Dr. R.A. Mashelkar
President

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Foreword

The Indian National Science Academy (INSA), New Delhi, is the adhering body in India to the International Council for Science (ICSU) and its affiliated International Unions / Committees / Commissions, etc. A joint National Committee of IGBP-WCRP-SCOPE, formed by INSA, looks after and supports the activities and implementation of various projects in these areas. The Committee comprises Drs. S.R. Shetye, B.M. Reddy, R. Navalgund, G.B. Pant, S. Devotta, S. Krishnaswami and J.S. Singh (Chairman). The Committee decided that a series of status reports be prepared on specific topics by leading Indian experts so that Indian work could be highlighted at various fora and general awareness be created among scientists and science students.

Humanity lived in harmony with nature until the industrialization began in the middle of the nineteenth century. Rapid industrialization took place to meet the ever-growing demands to raise living standards and comforts of life. It led to the human interference with the global climate. While the levels of greenhouse gas abundances in atmosphere fluctuated, particularly between ice and non-ice ages, the rates of their increase in the last century-and-a-half are unprecedented in the Earth's history leading to Global (Climate) Change. Concerned over the consequences of 'Global Change' the humanity became curious to understand the 'Biogeochemistry of the Earth system' in its totality. The most appreciated consequence is its impact on regional climate forcing mechnaisms and the associated biogeochemical processes, which is the most relevant to South Asia.

The Asian Monsoon is a unique climate force and the most significant tropical system in the world, on which the regional economy and food resources are heavily dependent. The Monsoon associated processes not only drive agriculture industry in South Asia but also biogeochemical processes on land and in the surrounding seas. Although the 'monsoon' is the primary driving force of the regional biogeochemistry, alterations in its intensity and coverage, due to global change, can cause changes on the rates of these processes and land-atmosphere-ocean feedbacks. Therefore, it is fundamental to understand the biogeochemistry of this region with a holistic view. Furthermore, it is important to recognize that not only the geographical setting of the North Indian Ocean is different from its counterparts in the Pacific and Atlantic Oceans but also the oceanic processes are distinctly different between the two of its basins, the Arabian Sea and the Bay of Bengal.

The present booklet dealing with 'Ocean Biogeochemistry' is the first in the IGBP-WCRP-SCOPE series. This booklet highlights the characteristics of ocean biogeochemical processes in the North Indian Ocean, with special reference to land-atmosphere-ocean interactions. I hope this contribution will prove useful to the students, academicians, researchers, and other interested in biogeochemistry and climate of our region.

[R.A. Mashelkar]

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Preface

Oceans cover 71% of the earth surface area and contain more than 97% of all water on the planet. Their capacity to store and redistribute heat and water around the globe is of profound importance in maintaining the Earth's environment. The biogeochemical processes in the oceans, such as CO_2 uptake and release, exchange of biogenic trace gases, fluxes of particulate and dissolved organic carbon to different depths, variable bacterial activity and phytoplankton blooms, are critical to the global biogeochemical cycling. The extreme heterogeneity, a characteristic of the coastal zone, which harbors more than 50% of the human population, influences the carbon cycling and carbon storage at global scale. Human-driven changes in nutrient availability are known to increase the frequency of toxic algal blooms, development of hypoxia and anoxia, and changes in biomass and productivity. Bays are of particular interest for understanding the linkages between land and sea, as they are heavily impacted by human activity. Since the dynamics of the marine ecosystems are closely related to climate variability, changes in climate are bound to have a significant effect on marine ecosystems. For example, increasing load of CO_2 in the atmosphere will lead to increased CO_2 concentration in the upper layer and consequently will change the carbonate chemistry, affecting adversely the reef organisms. Also changes in temperature and circulation patterns will affect the geographical distribution of fishes, their prey and their predators. The cliamte over the Indian Ocean and the adjoining continents are extremely dynamic, with regular annual occurrence of monsoons; this makes the region one of the strongest with respect to Ocean-Atmosphere-Land interactions in the world. The occurrence of the Indian Ocean Dipole, the Indian Ocean equivalent of the El Niño, is an important feature connected to monsoon rainfall.

At the request of the IGBP-WCRP-SCOPE National Committee, Dr. M. Dileep Kumar, a pioneer researcher in the area of Ocean Biogeochemistry and Fellow of the Indian National Science Academy, agreed to briefly summarize, in this document, the work done in India on the biogeochemistry of the Northern Indian Ocean, putting the same in the broader perspective of Earth System Science.

I am sure the material provided here will be of use to scientists and science students interested in IGBP.

J S Singh
Chairman,
IGBP-WCRP-SCOPE National Committee

Biogeochemistry of the North Indian Ocean

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Outline

Biogeochemistry is a subject wherein geochemical and biological processes occurring in the upper layers of the Earth, including atmosphere, are studied together. Many of the climatically important gases influencing the Earth's radiation budget result from these processes occurring in hydrosphere, geosphere or atmosphere. Oceans form a major part of the hydrosphere on our planet. The Indian Ocean, unlike the Pacific and Atlantic Oceans, does not connect the two Polar Oceans and is special in its geological setting. Thus, the presence of landmass to the north of the Indian Ocean makes the seas surrounding India vibrant with the occurrence of tropical monsoons.

The North Indian Ocean is one of the most biologically productive regions due to mixing processes driven by summer and winter monsoons. Relatively higher production in the Arabian Sea than in the Bay of Bengal is a consequence of poor vertical mixing due to strong surface stratification in the latter basin. Higher biological productivity in surface waters leads to oxygen deficiency in middle layers of the water column. Bacterial decomposition of organic matter under oxygen deficient conditions is carried out through nitrate reduction (denitrification) in subsurface waters of the Arabian Sea. The Bay of Bengal waters experience near equal oxygen deficiency, as the high salinity-low oxygen watermasses are transported into this region from the Arabian Sea, but not active denitrification. Supply of eroded materials from the Indian subcontinent during heavy discharge periods facilitates removal of organic matter from the water column in the Bay of Bengal. The Arabian Sea assumes significance as it accounts for about 30% of the global midwater column nitrate loss. Differences in physical and biogeochemical processes between the Arabian Sea and the Bay of Bengal account for higher emissions of biogenic gases from the former region than from the latter. Emission of nitrous oxide from the North Indian Ocean, in particular, appears to account for >74% of its total release to atmosphere from the South Asia. This biogeochemically significant region now appears to be more sensitive as the coastal hypoxia occur regularly following the summer monsoon driven high productivity. Whether in coincidence with the hypoxia or not occurrence of plankton blooms (red tide etc.) not only appears to lead to fish mortality but also accumulation/emissions of gases such as nitrous oxide and dimethylsulphide.

Biogeochemical processes maintain climatic conditions conducive for the sustenance of life on this planet and provide resources demanded by the inhabitants. For instance, these are in forms of food, energy resources, minerals etc. Although we seem to have identified some major elements of biogeochemical cycles in the North Indian Ocean we are far from understanding the processes and turnover of materials in detail, more importantly quantitatively. While facing these challenges to improve the scientific knowledge we should learn to be prudent to support the maintenance of the health of the seas in our neighbourhood, in our own interest and that of our successors.

0.0. BIOGEOCHEMISTRY

Natural gases maintaining the global radiation balance are closely linked to biological processes at the Earth surface. The gases formed from carbon (carbon dioxide, CO_2), nitrogen (nitrous oxide, N_2O) and sulphur (sulphur dioxide, SO_2) are the most relevant. These are consumed or released during the production and transformations of biological materials. The budgets of C, N and S, on geological time-scales at the Earth surface, are maintained through their cycling in and exchanges among air-ocean-crust reservoirs. The study of understanding biological and geochemical processes that regulate chemical equilibria at the Earth surface can be broadly termed ‘biogeochemistry’. Geochemical processes that controlled chemistry and the nature of materials at the Earth surface, since the formation of our planet, have changed into biogeochemical processes after the emergence of life. The life on this planet evolved about 3.5 billion years ago, i.e. 1 billion years after the Earth formed. Before the origin of life the Earth’s atmosphere consisted of molecular nitrogen, and carbon and sulphur oxides (carbon monoxide (CO) being the most abundant). As the life began and photosynthesis continued to occur oxygen evolved continuously and accumulated in the planet’s gaseous envelope. The oxygen build up over the geological times resulted in its second most abundant gas (20%) status in the present day atmosphere. Removal of carbon monoxide from the early atmosphere through conversion and photosynthesis, including that of anoxygenic, helped in the sustenance of later (developed) life forms. At present, it is hard to identify a geochemical process that is not influenced by biologically produced compounds in air, water or crust. The biogeochemistry is receiving much attention in recent times because of the global warming and climate change concerns, and our eagerness to prevent further damage to the Earth ecosystems.

1. BIOGEOCHEMISTRY AND CLIMATE

1.1. *How biogeochemistry controls climate?*

The summer temperatures in several parts of India might make people wonder about the noise by scientists on the warming of atmosphere. At an air temperature of 45°C in summer a rise by a degree appears to be of little significance, as we are immersed in day-to-day problems. Nevertheless, it is important since the global warming indicates a rise in average temperature of the air, after accounting for day and night (time), and equator to polar (geographical) variations. The atmospheric temperature is found to have warmed by ~0.6°C over the last century. The normal average temperature of our atmosphere is about 15°C. Sustenance of this temperature facilitated the emergence of life on our planet in contrast to our neighbours. How is 15°C maintained here while the neighbouring planets are so warm? It is because of the fortuitous distance of the Earth from the Sun and the presence of trace abundances of greenhouse gases (e.g. CO_2, methane [CH_4], moisture [H_2O]) that facilitated the warming of atmosphere. However, the composition of air has changed considerably in the recent past. The major change is in the abundance of CO_2 that increased from ~150 ppm (pre-industrial, before the middle of the nineteenth century) to about 376 ppm (in 2003). Similar increase in other greenhouse gases (e.g. CH_4 from ~600 to 1750 ppb in 2003 and N_2O from ~230 to 317 ppb in 2003) as well has resulted in the presently much debated global warming.

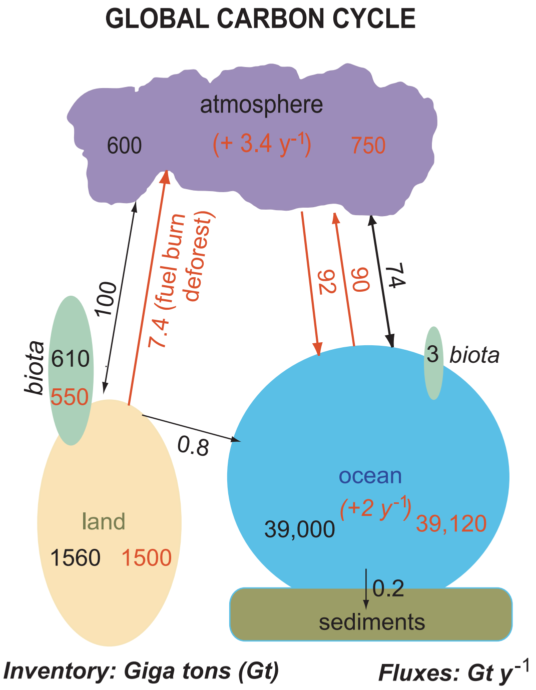

Figure 1. Global Carbon budget (after Siegenthaler and Sarmiento, 1993). Numbers in bold are preindustrial and normal font are those influenced by human activities. Numbers inside the earth compartments are the respective reservoir sizes and those next to arrows are rates of carbon transfer. Dark arrows indicate estimated rates for preindustrial era whereas light arrows account for anthropogenically modified rates. Numbers within brackets are the accumulation rates of anthropogenic carbon dioxide in atmosphere and oceans in Gt y^{-1} (Gt C = 10^{15} g C). The missing carbon of 2 Gt y^{-1} is that anthropogenic component for which the sink is expected in temperate coniferous forests. (See inside front cover for colour image)

A fundamental question is 'whether global warming is a new phenomenon?' A study of air trapped in Ice Mountains of Antarctica indicated a cyclical occurrence of lows and highs in carbon dioxide and methane associated with ice and non-ice ages, respectively, of the Earth during the last 400,000 years (Petit *et al.*, 1999). However, the carbon dioxide level fluctuated only between 180 and 280 ppm, well below the present level of 376 ppm. It is also the case with CH_4. These alarmingly higher levels of greenhouse gases in the present atmosphere are obviously the root cause of warming of atmosphere by ~0.6°C. Among CO_2,CH_4 and N_2O the first one is quantitatively the most important for the present warming. Although the other two have greater greenhouse warming potentials, on per molecule basis, the large abundance of CO_2 in the atmosphere makes it the primary cause.

While the presence of greenhouse gases helped maintain the surface temperatures conducive for the evolution of life on this planet the biological processes helped in modifying the atmospheric composition that made plant/animal forms comfortable. In a way, both the Earth and its life forms appear to evolve continuously. The fluctuations in greenhouse gases during glacial and interglacial periods, as revealed by studies on Antarctic ice, are reflective of their climatic importance. As the sea levels fall during glacial periods CH_4 trapped as gas hydrates, in marine sediments under high pressures, become unstable and decompose. The released CH_4 is oxidized to CO_2 in the atmosphere and thus these two gases reach higher levels just before deglaciation when the air temperatures also rise. Consequent to the increased atmospheric temperatures the ice locked up mainly in Polar Regions melt with implications to global productivity patterns. Some biogenic components in atmosphere (sulphate aerosols produced from reduced sulphur gases such as dimethylsulphide [DMS]) can significantly increase the atmospheric albedo (the extent of reflectivity of solar radiation back to space) while some gases (CO_2, CH_4 and N_2O) trap heat.

1.2. How does human interference affect atmospheric composition?

The abundance of CO_2 in air is maintained through interactions with hydrosphere (water bodies, mainly the ocean), biosphere (mainly plants) and geosphere (mainly carbonate rocks). A look at the carbon inventory (Siegenthaler and Sarmiento, 1993) of the Earth system suggests that about 60 times more carbon to that in the atmosphere is in the ocean (Figure 1). The major process removing CO_2 from the atmosphere is photosynthetic production on land and in the ocean. As easy exchange of gases is facilitated across the air-water interface, oceans have been playing a major role in maintaining the atmospheric CO_2 levels. However, the CO_2 release, due to industrialization and deforestation, at a rate of about 7.4 Gt y^{-1} has resulted in additional ocean absorption of ~2 Gt y^{-1} while about 3.4 Gt y^{-1} is retained in the atmosphere. The remaining is expected to be taken up by land biota, mostly in temperate forests. If this man-made CO_2 is not absorbed by the natural carbon sinks of our planet (ocean and land) we could have experienced severe warming by now.

2. OCEAN BIOGEOCHEMISTRY

2.1. *What are ocean biogeochemical cycles?*

Most of the oceanic CO_2 is present in dissolved forms of carbonic acid (in equilibrium with gaseous component, CO_2), bicarbonate and carbonate ions, maintained through the equilibria

$$CO_{2(g)} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

The gaseous component is less than 5% of the total dissolved inorganic carbon, which in surface layers of the ocean remains in equilibrium with that in air. Therefore, an increase in sea surface temperature (SST) or acidity of rainwater would enhance the partial pressure of carbon dioxide (pCO_2) in seawater and can result in its increased emission from the ocean. These processes together with an estimated absorption of ~1/3 of the anthropogenic carbon from the atmosphere reflect the influence of ocean carbon processes on CO_2 levels in air. The carbon cycle also exerts a strong influence on oceanic cycles of nitrogen and sulphur and hence on their gaseous compounds. In this way the biogeochemical processes in the ocean modulate the atmospheric composition and thereby climate. Domains of ocean biogeochemistry include coastal areas such as estuaries (where rivers meet the sea), mangroves, salt marshes and other coastal wetland systems.

Nitrogen, phosphorus, silica and sulphur compounds are also consumed during the organic material formation in sunlit layers of the upper ocean. In many areas of the ocean, particularly in tropics, the availability of nitrogen compounds limits the primary production or plankton growth. It is well known that nitrogen and sulphur compounds serve important biochemical functions in organisms, whose tissues are largely made of carbon. Carbon, phosphorus and silica are also used to build skeletal (e.g. carbonates, apatite and opal, respectively) materials of some plankton and other organisms. Phytoplankton is the starting material for secondary (zooplankton) and tertiary (fish) life forms in the ocean. About 90% of the organic material produced is recycled in the surface mixed layer (a well mixed layer of the sunlit upper ocean separated from the deep by a strong vertical density gradient) because of microbial degradation (Figure 2). The remaining material sinks into subsurface layers (export flux) where it continues to decompose due to bacterial respiration. The skeletal debris, on the other hand, dissolves under high pressures (the pressure in the ocean increases by about one atmosphere for every 10 m increase in depth) in the deep ocean. The remnant organic (mostly <2% of that produced at surface) and skeletal materials reach ocean bottom and get deposited in sediments. Even after deposition in sediments these materials continue to be decomposed and dissolved due to which the materials are released back to seawater.

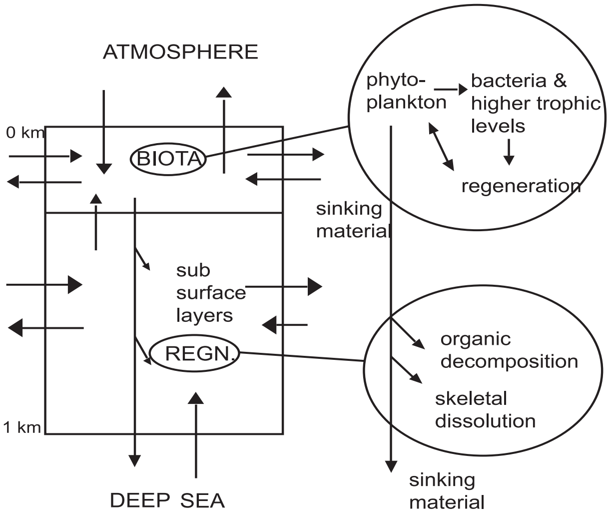

Figure 2. A schematic illustration of biogeochemical cycle in the oceans. Arrows indicate flows and directions of water and materials in horizontal and vertical directions in the water column. Of the total phytoplankton produced in surface layers a part will be transferred to bacteria and higher trophic level organisms, some other gets decomposed within the surface mixed layer and the remaining sinks into the deep ocean where it continues to undergo decomposition before being the rest deposited in sediments. While the organic material is bacterially decomposed that of skeletons gets dissolved under high pressures in the deep sea.

During the decomposition of organic matter dissolved oxygen is consumed according to the following reaction, which is exactly the opposite of that during primary production

$$(CH_2O)_{106}(NH_3)_{16} (H_3PO_4) + 138\ O_2 = 106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 122\ H_2O$$

The stoichiometry of C:N:P:O of 106:16:1:138 (normalized with reference to phosphate) is generally referred to as Redfield ratios (Redfield *et al.*, 1963). The same ratios approximately hold good for plankton and seawater (dissolved forms) but with some variations in time and space in the ocean. Any deviations from these ratios indicate shifts in biogeochemical systems. For instance, in regions where oxygen is in short supply the heterotrophic bacteria utilize nitrate as an alternative oxidant in the decomposition of organic matter due to which nitrate in seawater will be lower than expected from Redfield ratios. The oxygen deficiency is caused by its insufficient physical replenishment or removal by higher organic loads. Use of nitrate by bacteria leads to its reduction, a process known as 'denitrification', which involves the sequence

$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$

while the end product of this process is molecular nitrogen, an important intermediate is N_2O. In oxygen deficient regions where even nitrate is unavailable the bacteria utilize dissolved sulphate and reduce it to sulphide. Therefore, the sequence of oxidants utilized by bacteria during the decomposition of organic matter, depending on the free energies of reactions involved, is

$O_2 > NO_3^- > SO_4^{2-} > CO_3^{2-}$

Sulphate reduction is a common phenomenon in sediments and in polluted waters but is rare in oceanic water column. Carbonate reduction, on the other hand, occurs under extremely reducing conditions leading to CH_4 formation in marine sediments.

2.2. *What are major ocean biogeochemical properties and how do they change?*

The average depth of the oceans is about 3800 m. Circulation and biological processes largely govern the vertical variations (profiles) of dissolved substances in the oceans. While the mixing or circulation in the upper layers of the ocean is forced by wind that in the deep ocean is density driven. A layer in which a sharp decrease in temperature occurs immediately below the surface mixed layer is known as 'thermocline', below which also the temperature continues to decrease but slowly (Figure 3). Therefore, observing a vertical profile (or behaviour) of a property would enable us infer the processes controlling that property in the water column. The dissolved oxygen concentration (Figure 3) in the surface layers of the ocean is very high but decreases sharply across the pycnocline (a boundary where a strong gradient in density occurs - more or less in the region of thermocline). Higher concentrations of oxygen are maintained in the surface mixed layer because of its continuous exchange with atmosphere and its release during photosynthesis. At intermediate depths (about 200-1000 m) the oxygen levels remain low (the magnitude of which varies geographically) before it increases towards the bottom again. The zone or the layer of water containing minimal levels of oxygen (e.g. <10 µM in intermediate depths in the North Indian Ocean) is referred to as the 'oxygen minimum zone' (OMZ). Low levels of oxygen in the OMZ mainly result from its consumption during bacterial respiration. Oxygen increases towards bottom because of its supply through laterally spreading watermasses of polar origin. Surface waters of the polar regions are cold and hence absorb more oxygen from atmosphere, which first sink to deeper depths and then move laterally into tropical regions. The Antarctic Bottom Water (AABW) is the most important as it occupies vast areas of the bottom in world oceans.

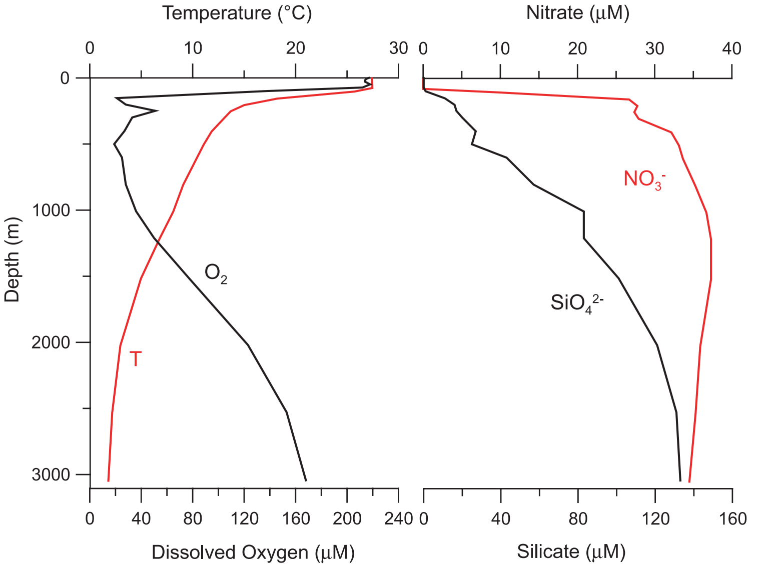

Figure 3. Typical vertical distributions (profiles) of temperature, dissolved oxygen, nitrate and silicate in the water column at 10°N and 67°E in the Arabian Sea. The thin water layer, at the top of the ocean, with near uniform levels in properties represents the surface mixed layer.

Nutrients (nitrate, phosphate and silicate) are low in surface waters as these are consumed during the biological production. Below the surface mixed layer their concentrations in seawater increase since the organic material decomposition occurs and the released materials accumulate in subsurface waters over time. However, the depths of occurrence of maximal levels of nitrate (soft-tissue nutrient) and silica (hard-tissue or skeletal nutrient) differ.

Nitrate reaches maximal values in the mid-layers of the ocean where bacterial decomposition and its non-utility are high. On the other hand, silica attains highest values in near bottom layers because of continued dissolution of skeletal opal, under high pressures, even after its deposition in sediments (Figure 3).

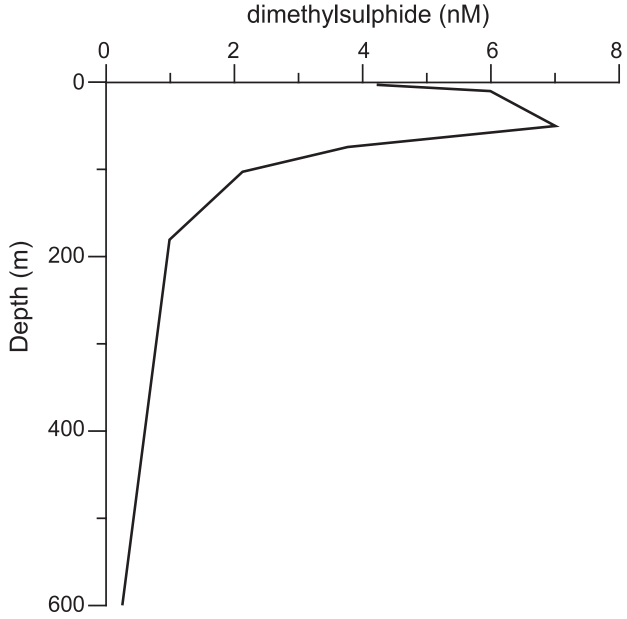

Figure 4. Typical vertical distribution of dimethylsulphide (DMS) in the water column at ~15°N and 71°E in the Arabian Sea.

The nutrients such as nitrate, phosphate and silicates are minor but sulphate is a major (>1 mg l^{-1}) ion in seawater. Therefore, variations in sulphate concentration due to biological processes are not significant. Hydrogen sulphide on the other hand occurs only in or near sediments or in coastal polluted waters. Nevertheless, a few reduced sulphur gases (DMS, carbonyl sulphide, methanethiol, carbondisulphide etc.) are formed during biochemical and photochemical processes in the surface seawater, of which DMS is the most important. Dimethylsulphide is formed from the decomposition of the parent compound dimethylsulphoniopropionate (DMSP). DMSP is expected to serve as an osmolyte, cryopreservative etc. but the clear physiological necessity of producing this compound by plankton is not clearly known. Therefore, DMS is largely restricted to the upper 200 m of the ocean below which it occurs at near or below detection limits (Figure 4). A potential product of DMS oxidation (and its possible sink in seawater) is dimethylsulphoxide (DMSO) that is found throughout the water column. Upon its emission and oxidation DMS produces sulphate aerosol in air that potentially can alter the Earth's reflectivity.

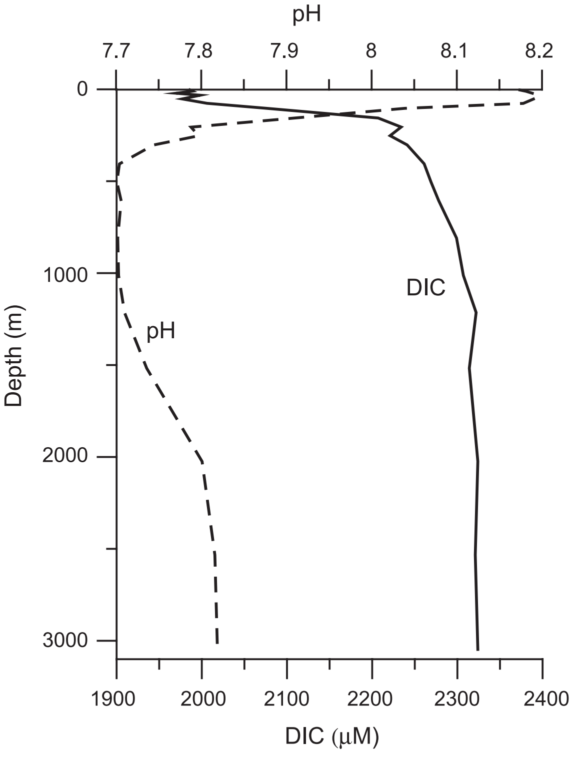

Figure 5. Typical vertical distributions of dissolved inorganic carbon (DIC) and pH in the water column at 10°N and 67°E in the Arabian Sea.

The most important and basic element of life is carbon, which occurs in seawater in dissolved and particulate phases in both inorganic and organic modes. Among all these, the dissolved inorganic carbon (DIC) is the most abundant that occurs in several forms as discussed above. Therefore, in seawater DIC is a sum of CO_2(g), H_2CO_3, HCO_3^- and CO_3^{2-}. Figure 5 depicts a gradual increase in DIC with depth in the ocean. While this is mostly due to organic material decomposition in the upper 2000 m the dissolution of carbonate skeletal materials (calcite and aragonite) is important in the deep and bottom layers of the water column. On the other hand, the gaseous component, pCO_2, exhibits a peak in subsurface layers because of its release during the organic tissue decomposition by bacteria. The properties pH and total (or titration) alkalinity (a measure of protons required to neutralize mainly carbonate ions) are closely linked to carbon chemistry in seawater. The vertical distributions of pH (Figure 5) and total alkalinity in the ocean mimic that of oxygen with a high in surface waters and a low in intermediate depths followed by a rise in deep and bottom waters. The pH and pCO_2 are interdependent variables. In fact, the HCO_3^- and CO_3^{2-} couple is mostly responsible for maintaining pH in seawater.

2.3. *Are there other important components in biogeochemical cycles?*

Besides the C, N, P, Si and S discussed above many other elements are also involved in biogeochemical cycles of which metal ions assume special significance. Some metal ions are essential requirements in physiological functions of organisms. Non-availability of such metals shall limit primary production. For instance, scarcity of iron in high nutrient – low chlorophyll (HNLC) regions (polar regions, in particular) is known to limit photosynthetic fixation. This is confirmed when laboratory experiments showed increase in primary production in these waters with the external supply of iron. This ‘iron fertilization’ technique has been favoured in recent times for the removal of human induced CO_2 from atmosphere into the ocean through enhanced primary production. Similarly, Zn, Cu, Se, V and Mo are useful in certain biochemical functions. Dissolved metals also support oxidation-reduction reactions in the environment. The most important in this context is the utilization of oxyhydroxides of iron and manganese during the decomposition of organic matter. These redox processes can occur both in oceanic water column and sediments.

3. THE NORTH INDIAN OCEAN

3.1. *Why is the North Indian Ocean important for biogeochemistry and climate studies?*

The climate over the North Indian Ocean and the adjacent continents, where regular monsoons occur annually, is one of the most dynamic in the tropical regions of the world. The population in this region mainly depends on the agriculture sustained by the monsoon rainfall. The strength of the southwest monsoon, in particular, determines the intensity of rainfall over the land. The monsoon strength, however, is a function of ocean-atmosphere interactions not only in this part of the world but also remotely affected by physical processes elsewhere (e.g. the El Nino-Southern Oscillation (ENSO) in the Pacific Ocean). There is widespread concern on how the global warming will affect the monsoon rainfall over India. Another important feature connected to monsoon rainfall is the Indian Ocean Dipole (IOD), an Indian Ocean equivalent of the El Nino (Saji *et al*., 1999). Occurrence of well separated region of warmer sea surface temperatures (SST) in the west from that of cooler SST area in the east in the south Indian Ocean is referred to as IOD. Besides, the Bay of Bengal is well known for the development of many low-pressure systems triggered by sea surface temperatures in excess of 28°C (Gadgil *et al*., 1984). The strong thermohaline stratification favoured by the freshening of surface water together with weaker winds over the Bay of Bengal (Shenoi *et al*., 2002) plays a key role in the development of such low pressure systems as compared to the Arabian Sea which receives less freshwater supply.

The extent of oceanic CO_2 uptake can be altered by changes in biogeochemistry of the surface ocean and/or climate. Further, atmosphere and rivers transport clay minerals that provide ‘continental connection’ to carbon cycle in the Bay of Bengal, that facilitate rapid scavenging of organic carbon from the water column. Nutrient inputs from atmosphere and rivers, besides that from low entrainment across the pycnocline, promote carbon fixation in the surface waters thus making the surface waters of the Bay of Bengal a seasonal sink for atmospheric CO_2 (Kumar *et al*., 1996). The Arabian Sea on the other hand acts as a perennial source (Sarma *et al*., 1998). Exhibiting a different behavioural pattern, N_2O is emitted in large quantities from all parts of the North Indian Ocean where the Arabian Sea is three times a stronger source than the Bay of Bengal (Naqvi and Noronha, 1991; Naqvi *et al*., 1994). Aerosol levels have been found to be higher over the Arabian Sea in winter but atmospheric nitrogen supply is far less than by the upward supply across the thermocline (Sarin *et al*., 1999). Thus, there are several unique aspects of biogeochemical cycling that make the North Indian Ocean one of the most vibrant and important regions in the world oceans vulnerable to global change.

3.2. *What is the South Asia monsoon - climate system?*

The Asian monsoon system comprises South Asia, Southeast Asia and East Asia sub-systems. The South Asia monsoon system drives strong interactions among land-atmosphere-ocean in the region. This monsoon system operates (Pant and Rupa Kumar, 1997) through regular oscillations in the Tropical Convergence Zone (TCZ); a latitudinal zone where air masses of inter-hemispheric origin or those within northern hemisphere converge. The convergence zone shifts across the equator seasonally and is largely determined by the Earth rotation and insolation. During June to September (the summer season) the TCZ moves north of equator and draws winds from south that actually become southwesterly after crossing the equator (Figure 6). At this time northern hemispheric winds also converge over India. The summer winds together with the associated rain is referred as summer (southwest) monsoon. Surface winds in the North Indian Ocean reach maximal speeds of 18 m s^{-1} (climatological mean) in July, particularly in the western Arabian Sea. Intense rainfall over the Indian subcontinent results in immense freshwater and sediment discharges into the neighbouring seas, particularly into the Bay of Bengal. On the other hand, winds blow from north to south in winter since the TCZ moves to the southern hemisphere (Figure 6). This brings cold dry winds from the north to the Indian Ocean region. The period between November and February is referred as winter (northeast) monsoon. Transitional periods between these two monsoons are known as intermonsoon seasons of which the one following summer monsoon (post-southwest monsoon) is usually marked by development of atmospheric disturbances over the Bay of Bengal (Murty *et al*., 2000). The occurrence of monsoons and occasional low pressure systems over the Indian Ocean make this region one of the strongest with respect to ocean-atmosphere-land interactions.

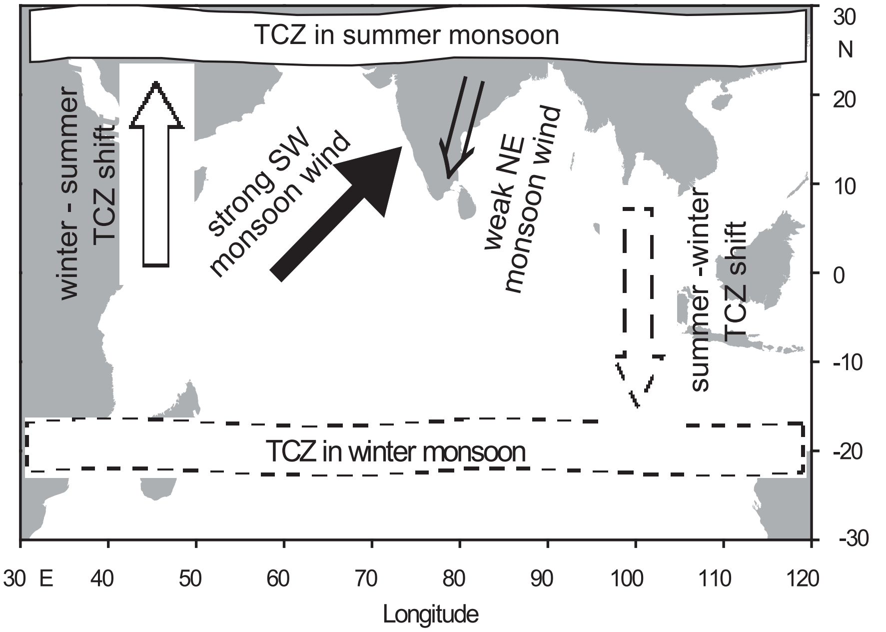

Figure 6. Schematic diagram depicting semi-annual shifts in Tropical Convergence Zone (TCZ) over the Indian Ocean. Wintertime position of TCZ and direction of movement are shown with dashed lines. Continuous lined objects are for summer monsoon. Closed and open arrows indicate strengths and directions of winds in respective seasons.

3.3. *How circulation and mixing in the North Indian Ocean are influenced by monsoon?*

Physical processes in the ocean change with seasons in the upper 1000 m or so. The circulation in the upper few 100 m is largely driven by changes in winds whereas vertical mixing in the ocean is by changes in density. The latter is known as thermohaline circulation. Coastal currents become more significant during monsoons. In summer monsoon West India Coastal Current (WICC, Shetye, 1998) flows southward and joins the eastward flowing Summer Monsoon Current (SMC), which carries high salinity waters into the Bay of Bengal (Shankar *et al*., 2002). The reverse occurs in winter as the low saline surface water flows southward in the Bay of Bengal and cover large parts of the southern Arabian Sea. The winter coastal current flowing along India and Sri Lanka in the Bay of Bengal is known as East India Coastal Current (EICC, Shetye *et al*., 1996) the direction of which changes with season (Shankar *et al*., 2002).

Vertical mixing between surface and subsurface waters is prominent in the Arabian Sea than in the Bay of Bengal. Water budgets indicate that the Arabian Sea is a negative water body (where total influx [= precipitation + river flows] is less than total out flux [= evaporation]). As the Arabian Sea is more saline several watermasses form and flow at various depths (Wyrtki, 1971, Kumar and Li, 1996); the Arabian Sea High Salinity Water (ASHSW) flows in the upper layers, the Persian Gulf Water (PGW) results from the subsurface outflow from the Persian Gulf and flows around 200-300 m, and the Red Sea Water (RSW) originates from the waters flowing out of the Red Sea and occupies 600-800 m. In addition, North Indian Deep Water (NIDW) forms as a mixture of these three high saline waters and flows southward, which has a strong influence in the South Indian Ocean processes. Waters originating in circumpolar regions dominantly occupy the deep and bottom layers (particularly below ~2000 m) in the Indian Ocean. The Modified North Atlantic Deep Water (MNADW, originally formed in the Norwegian Seas) occupies the deep layers whereas the AABW dominates in bottom waters. The structures of vertical profiles of temperature and salinity in the North Indian Ocean are defined by mixing of these watermasses and also the Bay of Bengal Low Salinity (BBLS) water (Kumar and Li, 1996). Intense river water discharge into the Bay of Bengal ($1.6 \mathrm{X} 10^{12}$ m^3 y^{-1}) from the Indian subcontinent, following monsoon rainfall during the southwest monsoon, makes the surface waters of the Bay fresher and not conducive for high-density watermass formation. The surface waters of the Eastern Indian Ocean are strongly influenced by precipitation over this region whereas the subsurface layers are affected by Indonesian Throughflow Waters (ITW) entering through the Indonesian Archipelago.

3.4. *Why is vertical mixing different in the upper layers of the North Indian Ocean?*

The signatures of monsoons of the South Asia are strongly felt in the physical and the consequent biogeochemical processes occurring in the North Indian Ocean. Strong winds blowing parallel to the coast in the summer monsoon force the surface waters hugging the coastal regions to move away from the shore. Replacement of these waters occurs by drawing those from intermediate depths to surface. This process is known as upwelling. Globally important upwelling regimes found in the Arabian Sea are Somali and Oman upwelling systems. Besides, upwelling occurs also along the southwest coast of India (eastern Arabian Sea); the processes associated with this system appear to be more complicated and ecologically significant (Panikkar and Jayaraman, 1966) than probably in any other region in the world. Particularly, upwelling in the eastern Arabian Sea appears to be caused by forces other than local winds (Panikkar and Jayaraman, 1966; Shankar *et al*., 2002). Upwelling, therefore, brings subsurface waters to surface and facilitates easy exchange of temperature and other properties between these layers. Very low river discharge ($0.3 \mathrm{x} 10^{12}$ m^3 y^{-1} or about 1/3 of that by Ganges and Brahmaputra discharges; Shankar and Shetye, 1997) into the Arabian Sea does not seem to affect the upwelling. While the upwelling process is dominant in the Southwest monsoon the convection process is significant in winter monsoon (Madhupratap *et al*., 1996). The cold and dry air blowing from the north enhances evaporation over the Arabian Sea. Consequently, the surface water becomes denser and sinks to appropriate density horizon. Such sinking sets up convective (thermohaline) circulation, particularly in the Northern Arabian Sea basin, due to which nutrient and CO_2 rich cold subsurface waters are lifted to the surface (Figure 7). Thus, the entrainment (exchange of properties during mixing between surface and subsurface layers) occurs in both the monsoons in the Arabian Sea that facilitates transfer of heat, absorbed by the surface ocean, to deep waters.

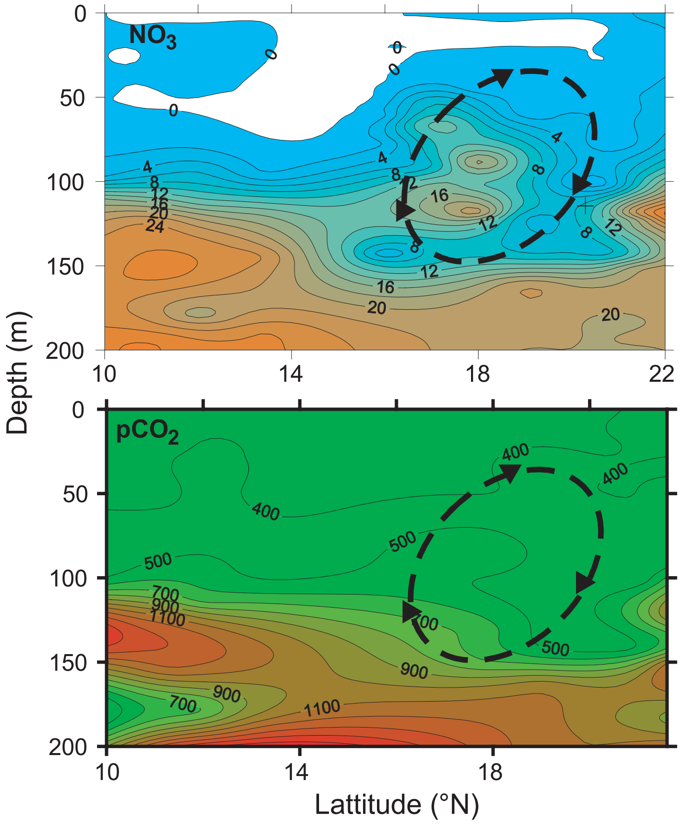

Figure 7. Effect of winter convection on biogeochemical properties (Nitrate (µ M) and pCO$_2$ (µ atm)) in the coastal waters of the northwest India. Sinking of high density surface waters due to higher evaporation in winter sets up a convective circulation (as shown by direction of arrows) in which subsurface waters rise to the surface. Nutrients brought to surface promote biological production in the Arabian Sea in winter.

In contrast, the vertical mixing across the thermocline is constrained in the Bay of Bengal. Neither upwelling nor convection is prominent in this region. Summer upwelling along the east coast of India is weak due to simultaneous downwelling caused by Ekman pumping (wind driven) over the Bay of Bengal and remote forcing from the Equator (Shetye *et al*., 1991). Although upwelling and convective processes are reported to occur in Southwestern regions of the Bay of Bengal (Vinayachandran and Mathew, 2003) these are much weaker than in the Arabian Sea. Thus, the strengths of upwelling and convective processes in the Bay of Bengal are not strong enough to force effective entrainment of properties between surface and subsurface waters. Eddies may supply nutrients to surface layers in the Bay (Prasannakumar *et al*., 2004) the quantitative significance of which is yet to be ascertained. The major processes of physical-chemical-biological coupling are schematically shown in Figure 8. The solar heat absorbed by the Bay of Bengal remains in the surface layers, without being transferred to deep waters, facilitating the development of atmospheric disturbances; i.e., low-pressure systems are more prominent and frequent over the Bay of Bengal than over the Arabian Sea. Occurrence of frequent atmospheric disturbances, due to prevailing freshwater lens and low winds, results in more rainfall and subsequent river discharge that

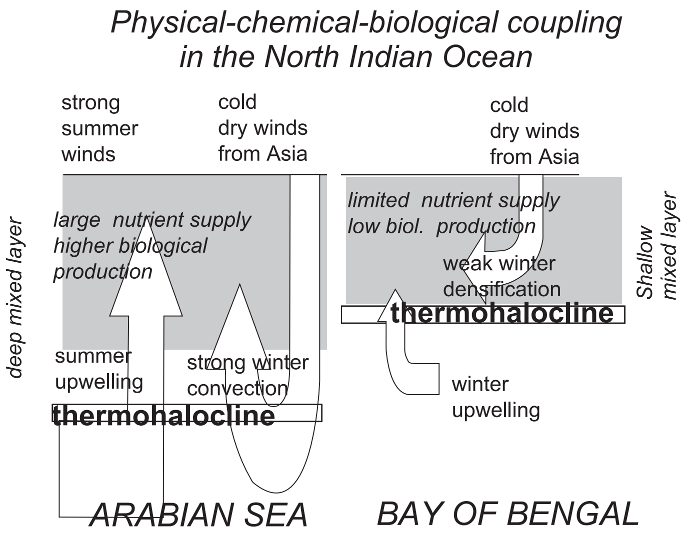

Figure 8. Summary of various physical mechanisms and their degrees of influence on the supply of nutrients to surface waters with implications to biological production in summer and winter seasons in the North Indian Ocean (Schematic).

again promote disturbances; a system similar to a 'do' loop indicating positive feedback (Figure 9). Biogeochemical processes in the North Indian Ocean are driven by monsoons and hence it is apt to name the present subject as the 'Monsoon biogeochemistry'.

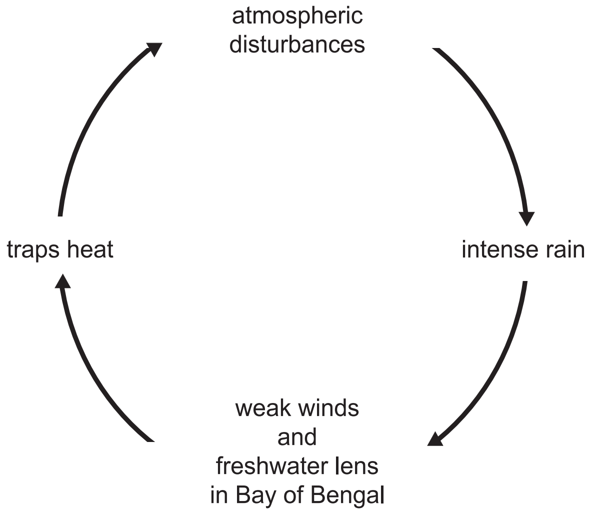

Figure 9. Relations between low salinity lens (fresher water) at the surface of the Bay and the atmospheric disturbances (storms, cyclones etc.).

3.5. *Is there a difference in biological production?*

Nearly five decades ago Panikkar and Jayaraman (1956, 1966) pointed out the differences in biological productivity and fish landings in waters on either side of the Indian peninsula, and attributed the differences to distinct hydrological processes. Strong regional and temporal variability in physical forcing in the North Indian Ocean translates into an even larger variability in biological productivity patterns and species diversity. We now have a reasonable idea of general productivity trends just in terms of chlorophyll; thanks to satellite remote sensing tools that enable us appreciate basin wide features. However, we are far from understanding biological diversity and trophic successions both qualitatively and quantitatively. The inadequate knowledge of this very first part of the biological pump limits our precise understanding of quantitative transfer of biological carbon and its turnover in the Indian Ocean.

The basin wide productivity patterns have been revealed by International Indian Ocean Expedition (IIOE) results; the near surface (1 m) production has been estimated to be higher in the Bay of Bengal (by 1.25 times than in the Arabian Sea) but the total column production is less (Qasim, 1977) because of the low nutrient supplies (Figure 8). Recent measurements revealed a maximal photosynthetic fixation of 1229 mg C m^{-2} d^{-1} off Chennai in the Bay of Bengal (Madhu *et al.*, 2002), which is a consequence of the 1999 Orissa super cyclone. Winter bloom production (Vinayachandran and Mathew, 2003) seems to occur largely in the southwestern Bay of Bengal (Chlorophyll *a* of 0.5-1 mg m^{-3}). Primary productivity, however, does not exhibit strong seasonal variability. Rather, episodic peaks in carbon fixation in the Bay of Bengal are driven by extreme climatic events (Madhu *et al.*, 2002).

Maximal production in the eastern Arabian Sea of 1782 mg C m^{-2} d^{-1} occurs in southwest monsoon (Prasannakumar *et al.*, 2001). The rates of fixation show strong spatial and seasonal dependency in the Arabian Sea, with highest value of 2668 mg C m^{-2} d^{-1} in the western region during the summer monsoon (Owens *et al.*, 1993). Winter convection over a wider region in the north Arabian Sea results in very high organic matter production. The recent JGOFS experiments in the Arabian Sea showed the production in winter to be much larger than thought earlier (Madhupratap *et al.*, 1996; Barber *et al.*, 2001) and that we are still far from realistic estimates of total carbon fixation, even in the supposedly best studied region (the Arabian Sea) of the Indian Ocean. Regular occurrence of summer upwelling and winter convection processes efficiently pump nutrient laden subsurface water into the surface layers in the Arabian Sea. Availability of nutrients facilitates very high biological production in the Arabian Sea (Bhattathiri *et al.*, 1996). Lateral advection of upwelled waters from western region to central Arabian Sea has been found in summer (Prasannakumar *et al.*, 2001) that makes central parts of the Arabian Sea more productive in summer. Satellite derived productivity pictures (Figure 10) reveal strong variability in biological production in the Indian Ocean, north of the Equator in particular, and that our neighbourhood is one of the most productive regions in the world oceans. Qasim (1977) estimated total column primary production to be 4.42×10^{15} gC y^{-1}, secondary production to be 69×10^{12} gC y^{-1} and tertiary production or potential exploitable yield to be 15-17×10^{12} gC y^{-1} in the Indian Ocean. Based on these estimates Qasim (1977) computed a transfer coefficient of <10% from one to the next higher trophic level.

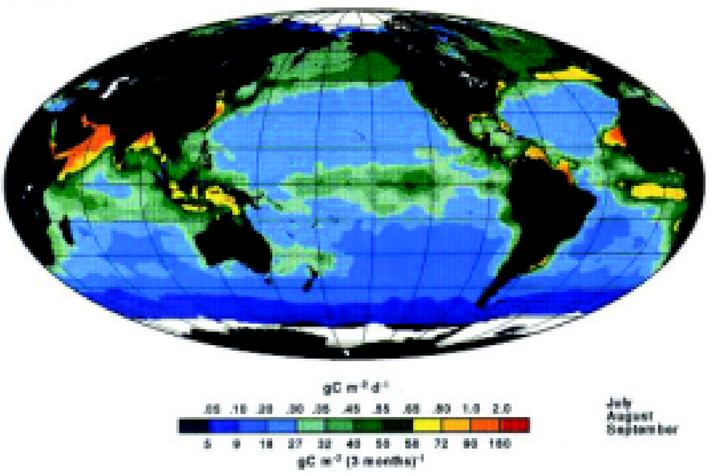

Figure 10. Satellite derived imagery of primary production in the world oceans during summer (from Behrenfeld and Falkowski, 1997). The North Indian Ocean is one of the most productive regions in the world where the Arabian Sea fixes more carbon than the Bay of Bengal. Regional trends observed in the above picture are more or less the same in all seasons but with changes in magnitudes. (See inside front cover for colour image)

One of the most recent findings of the Arabian Sea biogeochemistry has been the occurrence of seasonal hypoxia along the west coast of India (Naqvi *et al*., 2000). Systematic observations have shown that hypoxia occur in waters of the eastern Arabian Sea in the months following the southwest monsoon. As the upwelling promotes coastal biological production the column production in some places in summer reaches over 2 g m^{-2} d^{-1} along the west coast (Bhattathiri *et al*., 1996). Such an intense production in upwelled water, that is originally depleted in oxygen as it is drawn from OMZ, demands enhanced oxidant supply to support the bacterial respiration. Prevalence of low oxygen conditions together with low salinity cap at the surface in September-October period leads to hypoxia and the subsequent reduction of nitrate (denitrification) in the subsurface layers. Therefore, low salinity lens formed due to river discharges into the Bay of Bengal and Arabian Sea significantly influences climatic (in the Bay) and biogeochemical (in both the regions) processes as depicted in Figure 11. Consumption of nitrate results in its depletion that can limit phytoplankton production. Non-availability of nitrate then leads to the occurrence of nitrogen fixing plankton. Usually blooms of *Trichodesmium* (Devassy *et al*., 1978) or *Noctiluca* (Sahayak *et al*., 2005) occur. During the denitrification, like in nitrification, N$_2$O is an intermediate compound (Naqvi and Noronha, 1991). Occurrence of hypoxia in coastal waters of Goa is hypothesized to be linked to drainage of agricultural wastes into nearshore waters (Naqvi *et al*., 2000). Although possible, enrichment of nutrients in coastal waters, particularly off river mouths, is not known. Moreover, we have no records to show that coastal biological production has increased in recent times in proportion to nitrogen loads into the coastal ocean. Despite the fact that the marine fish catch shows excellent relation with the amounts of nitrogen fertilizer consumed in India in the second half of the last century (Figure 12; Kumar, 2004) it is premature to support the fertilizer stimulated productivity, to

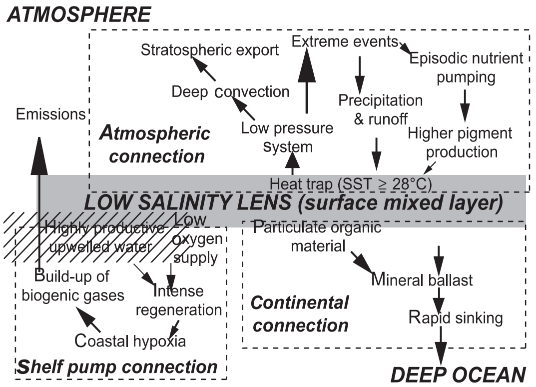

Figure 11. Schematic presentation of influence of Low salinity lens (LSL) on ocean climate and biogeochemical cycles with particular reference to air-sea-land connections. In the atmospheric connection the prevalence of lens at the surface leads to development of low pressure systems (atmospheric disturbances) due to which biological production increases. Discharge of suspended solids along with fresh water by rivers (Continental connection) strengthens mineral ballast and increases sinking speeds of organic matter. Reducing the atmospheric oxygen supply because of low saline layer at the top results in development of suboxic waters in shelf regions that potentially accumulate biogenic gases (Shelf pump connection).

be the cause of hypoxia, as there are several missing links including the evidence for increased primary production in coastal waters.

3.6. *Are the sinking fluxes related to biological productivity?*

Higher productivity does not result in higher sinking fluxes in the Arabian Sea than in the low productive Bay of Bengal (Nair *et al*., 1989; Ittekkot *et al*., 1991). Sinking organic carbon is higher in the Bay of Bengal because of its association with clay minerals (Table 1). River and atmospheric transport of mineral materials and their faster sinking, in view of higher density, facilitates rapid scavenging of organic carbon aggregates from the water column. This is referred to as 'continental connection' or 'mineral ballast' (Figure 11) in the ocean (Ittekkot *et al*., 1991; Kumar *et al*., 1998). Besides the association between mineral and organic materials, sinking fluxes seem to be regulated by plankton diversity. For instance, sinking is faster in the western Arabian Sea because of the large sized diatom prevalence than in the eastern parts. Furthermore, less amount of organic carbon reaching the sea floor in the Arabian Sea, in its eastern part in particular, than in the Bay of Bengal is also because of the net heterotrophic nature, which is again more intense in the eastern Arabian Sea (Sarma, 2004). Occurrence of denitrification at intermediate depths is indicative of the intensity of heterotrophic nature of the Arabian Sea. The rapid deposition of labile or degradable organic carbon at the bottom and its continued regeneration results in the release of nutrients to water column in the benthic layers. The lateral advection of released materials makes the Bay of Bengal a strong source of nutrients to the South Indian Ocean (Broecker *et al*., 1980).

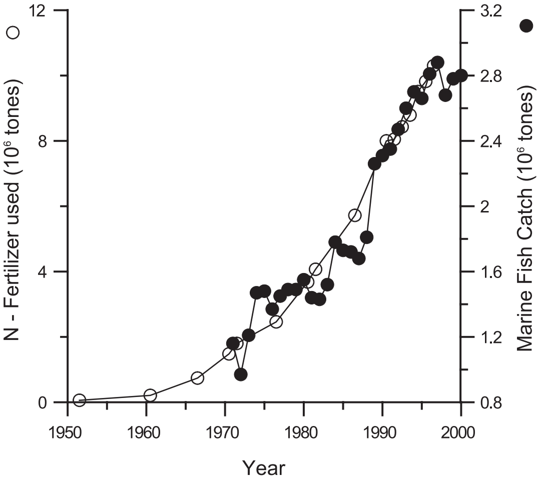

Figure 12. Increases in nitrogen fertilizers used and marine fisheries production in India in the last few decades (data from Agarwal and Narain, 1999; FAO, 1981, 1990, 2002; after Kumar, 2004).

Table 1. Sinking fluxes of carbon and clay particles in the North Indian Ocean.

Area/position	Flux (g m^{-2} d^{-1})		
	Organic carbon	Carbonate carbon	Clays
Bay of Bengal (Ittekkot *et al*., 1991)			
North (17°26'N)	2.65	1.29	27.96
Central (13°09'N)	2.61	2.03	14.70
South (04°26'N)	2.04	2.22	8.56
Arabian Sea (Nair *et al.,* 1989)			
West (60°30'E)	1.80	2.28	2.64
Central (64°45'E)	1.53	2.10	3.05
East (68°45'E)	1.56	1.43	5.40

3.7. *How intense is oxygen minimum in the North Indian Ocean?*

Very high biological production at the surface and the subsequent bacterial decomposition of organic matter results in heavy oxygen demands in the water column. Therefore, oxygen levels at intermediate depths reduced to near detection limits in the North Indian Ocean (Sen Gupta *et al*., 1976; Sen Gupta and Naqvi, 1984). Despite the lower biological production in the Bay of Bengal than in the Arabian Sea how are the low oxygen values nearly similar between the two regions? Electron Transport System (ETS) measurements (Figure 13) revealed that the bacterial respiration rate is much higher in surface and subsurface layers of the Arabian Sea than in the Bay of Bengal (Naqvi *et al*., 1996). This difference could have been caused by faster scavenging of organic matter from the Bay of Bengal water column, aided by the continental ballast. In view of the rapid particulate organic matter removal (Table 1) and lower bacterial respiration (Figure 13) one would expect at least marginally higher oxygen levels in intermediate waters of the Bay of Bengal. But the oxygen levels are nearly equivalent. Extreme low levels in the Arabian Sea intermediate layers could also be ascribed to the possibility of poor replenishment of oxygen, due to the expected sluggish mixing forced by the presence of Asian landmass. However, recent calculations revealed that the mixing is indeed rapid; turnover time of waters in intermediate layers is about 1-10 years in the Arabian Sea (Somasundar and Naqvi, 1988; Sarma *et al.*, 2003). Therefore, intense biological pump and high bacterial respiration account for the extremely low oxygen levels in the Arabian Sea. On the other hand, low oxygen levels in intermediate layers of the Bay of Bengal, despite lower productivity and respiration rates, appear to be due to the lateral transportation of oxygen deficient high salinity watermasses from the Arabian Sea at subsurface depths (Naqvi *et al.*, 1994, Kumar and Li, 1996) and oxygen consumption, in situ.

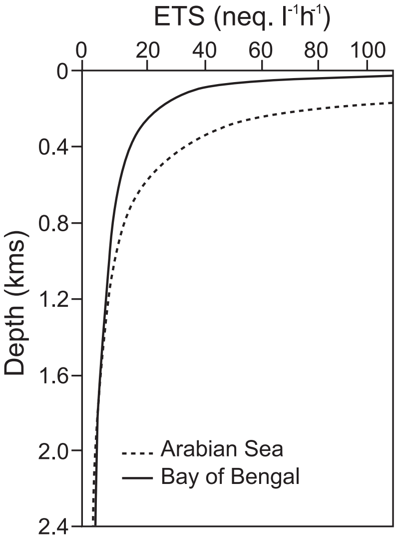

Figure 13. Comparison of Electron Transport System (ETS) rates, a measure of bacterial respiration, in the North Indian Ocean (from Naqvi et al.*, 1996).*

3.8. *How significant is the water column denitrification in the Arabian Sea?*

Very low levels of oxygen, below 25 μM (or 0.5 ml O_2 l^{-1}), force heterotrophic bacteria to turn to nitrate as the next alternative oxidant. This process is predominant in intermediate layers and is characterized by the presence of secondary nitrite maximum (Sen Gupta *et al.*, 1976). The primary nitrite maximum occurs close to the upper boundary of the thermocline and is due to nitrification during organic matter regeneration. A measure of denitrification in the water column is nitrate deficit; defined as the difference between expected nitrate released during the organic material decomposition (based on theoretical Redfield ratios) and the sum of nitrate and nitrite observed. The denitrification is very prominent in the North Arabian Sea with considerably higher nitrate deficits (upto 12 μM) found where the layer of water column experiencing denitrification is also thick (~500 m between 150 and 700 m). This layer becomes thin and nitrate deficit decreases from North to South and from East to West in the Arabian Sea (Naqvi *et al.*, 1993). Occurrence of the secondary nitrite together with positive nitrate deficits (signs of active denitrification) are confined to the north of 10°N in the Arabian Sea. This horizontal variation in denitrification (Figure 14) indicates the delinking of intense denitrification region in the east with the high biological production area of the western Arabian Sea (Naqvi, 1991). This is consistent with the recent observation that the eastern Arabian Sea is more heterotrophic than its western counterpart (Sarma, 2004). The Arabian Sea, which is <2% of the total oceanic area, assumes global significance as it accounts for 40% of the total pelagic denitrification occurring in the world oceans (Bange et al., 2005). The remaining occurs mostly in large areas of the eastern tropical Pacific Ocean. The estimate of ~30 Tg N y^{-1} (Tg = 10^{12} g) of water column denitrification in the Arabian Sea (Naqvi, 1991) appears to be underestimated since Bange *et al.* (2005), based on latest information available, evaluates this to be ~60 Tg N y^{-1}, against a global estimate of ~150 Tg N y^{-1}.

Evaluations also indicated positive nitrate deficits not only in the southern Arabian Sea but also in the Bay of Bengal (Naqvi *et al.*, 1994) and Andaman Sea (Kumar, 2001) regions. However, the fact that no secondary nitrite is found in regions other than the North Arabian Sea testifies that active denitrification does not occur in the water column elsewhere in the Indian Ocean. What might have resulted in the occurrence of positive nitrate deficits in the rest of the Indian Ocean? As in the case of low oxygen spread, the horizontal advection is responsible for transporting intermediate waters of the North Arabian Sea, containing passive denitrification signatures, to other areas of the Indian Ocean. Nevertheless, the thickness of the OMZ and depth range of positive nitrate deficits is small in the Bay of Bengal than in the North Arabian Sea (Naqvi *et al*., 1994). Transportation of watermasses at intermediate depths from the Arabian Sea into the Bay of Bengal also accounts for higher levels of N_2O found in the latter region, in addition to that produced by nitrification, in situ. In the Arabian Sea, on the other hand, N_2O is formed both from nitrification and denitrification pathways. Importantly, N_2O is also consumed, simultaneously to its production, during denitrification in the Arabian Sea, which does not occur in the Bay of Bengal.

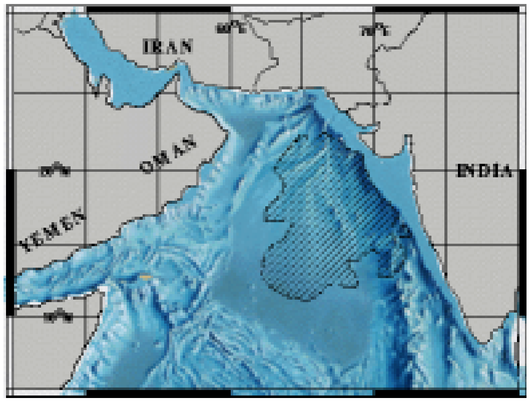

Figure 14. Shaded area indicates the region of active water column denitrification in the central and eastern parts of the Arabian Sea (after Naqvi, 1991). (See inside back cover for the colour image).

3.9. *What is the microbial loop in the Arabian Sea?*

The plankton produced in the sunlit layers is expected to support the higher trophic levels in the ocean. Secondary production appears to be adequately supported by the higher primary production in monsoon seasons. However, the primary production during intermonsoon periods is lower than during monsoons in the Arabian Sea. The bacterial biomass in terms of carbon is in excess of that of the phytoplankton during inter-monsoons (Ramaiah *et al*., 1996, Bhattathiri *et al*., 1996). Hence, in periods between the two monsoons the secondary production in the Arabian Sea appears to be mostly supported by microbes, through a process termed ‘microbial loop’. The prevalence of stable mass of zooplankton, in particular in the surface mixed layer, in all seasons despite the short supply of the phytoplankton substrate in inter-monsoon periods is known as ‘zooplankton paradox’ (Madhupratap *et al*., 1996).

3.10. *How does mineral matter help organic matter sink faster in the sea?*

As the continental connection results in mineral ballast that facilitates the rapid scavenging of organic materials from the oceanic water column it is important to examine the processes involved. Compositional studies of sinking particles indicated a strong association between organic carbon and clay minerals (Table 1). Higher organic carbon contents are found, in particles collected using sediment traps, when clay mineral particles are more suggesting that mineral ballast mechanism is active in the North Indian Ocean. Further evidence is found through a relation between the sizes of transparent exopolymer particles and the number of mineral particles associated (Kumar *et al*., 1998). More number of mineral particles are found associated with polymer particles in the Bay of Bengal. Sizes of these organic particles, which have been embedded with more mineral particles, are smaller in the Bay of Bengal than in the Arabian Sea where polymer particles are larger but contained less number of mineral particles (Figure 15). Therefore, large river and atmospheric inputs of terrigenous mineral materials have a strong influence on biogeochemical cycles in the ocean. This mechanism is of particular significance in the North Indian Ocean since it accounts for the differences in organic matter transports and water column reducing conditions (e.g. bacterial respiration) between the Arabian Sea and the Bay of Bengal.

3.11. *Are there regional changes in skeletal matter dissolution?*

In view of regional variations in the decomposition of organic matter it is interesting to examine whether such changes occur in the dissolution of skeletal materials as well or not. Indeed regional differences have been found in the extent of carbonate and silicate mineral dissolutions in the North

Indian Ocean. Higher amounts of carbonate minerals are found to dissolve in the northern and eastern areas than in southern and western regions of the Arabian Sea (Figure 16). Carbonate mineral dissolution is also higher in the Arabian Sea water column than that in the Bay of Bengal (George *et al*., 1994). These regional variabilities in carbonate dissolution in the North Indian Ocean are in excellent agreement with changes in the heterotrophic nature (intensity of bacterial activity during organic material decomposition). The heterotrophic or reducing nature, as stated in above sections, in the North Indian Ocean varies as:

In the Arabian Sea: North> East > West > South

In the Indian Ocean: Arabian Sea > Bay of Bengal

Why is the extent of carbonate mineral dissolution be associated with the heterotrophic nature of water column? As the bacterial respiration enriches seawater with CO_2 it can react with $CaCO_3$ according to

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2\ HCO_3^{2-}$$

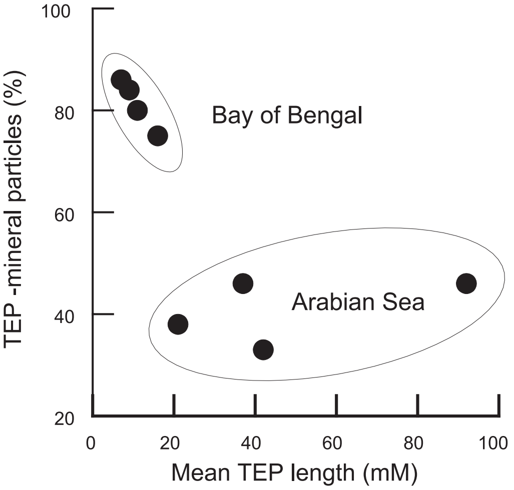

Figure 15. Relation between the mean lengths of transparent exopolymer particles (TEP) and percent TEP associated with mineral particles at about 500 m in the North Indian Ocean. Higher TEP-mineral association in the Bay of Bengal leads to the formation of small sized TEP from the breakdown of larger TEP. The extreme right side point in the Arabian Sea group was found at a location where a Phaeocystis *bloom occurred during the SW monsoon of 1996 (after Kumar* et al.*, 1998).*

Therefore, the regions of intense organic matter decomposition turn highly corrosive to carbonate minerals in the ocean. The two most common carbonate minerals produced by marine organisms are aragonite and calcite. These two have the same chemical composition ($CaCO_3$) but different crystal structures (polymorphs) and as such in dissolution patterns. Seawater is found to become undersaturated with respect to aragonite at shallower depths (in the upper 1000 m) than to calcite (> 3000 m) in the North Indian Ocean (Kumar *et al*., 1992; George *et al*., 1994). Interestingly, aragonite saturation depth in the Arabian Sea has become shallower in the last two decades by 16-120 m (Sarma *et al*., 2002), which is due to the absorption of anthropogenic CO_2 by the ocean. Close proximity of the North Indian Ocean to countries that are thickly populated and exploding with industrial developments is responsible for its quick absorption of atmospheric CO_2. The shallowing aragonite horizon in the Arabian Sea is the best indicator of how fast the biogeochemical system in the North Indian Ocean is responding to the invasion of anthropogenic CO_2 and hence helps us realize how sensitive our seas (surrounding India) are. Comparatively low dissolution of carbonate particles in the Bay of Bengal could be due to their coating with organic materials, scavenged from the water column. On the other hand, there are no significant differences in silicate dissolution between the Arabian Sea and Bay of Bengal. Importantly maximal silicate dissolution occurs in near bottom waters of the northern most parts of the Indian Ocean (Kumar and Li, 1996). Upward diffusion of the dissolved silicate from bottom/deep to surface layers and

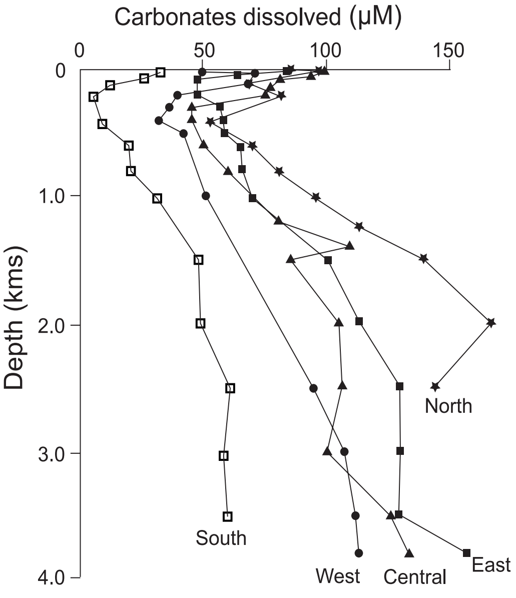

Figure 16. Regional variability in skeletal carbonate dissolution in the Arabian Sea (from Kumar et al.*, 1992).*

also its lateral transport to the South Indian Ocean makes the North Indian Ocean a significant supplier of silicate. Silicate concentrations of > 150 µM in near bottom waters of the northern parts of the Arabian Sea and Bay of Bengal rank among the highest found in the world oceans.

3.12. *What are seasonal hypoxia? Why do they occur?*

Eutrophication, abrupt high biological production, has become common in several places in the world oceans mainly because of pollution. Coastal pollution due to nutrient dumping triggers biological productivity since either nitrate or phosphate is often the limiting nutrient. Following the eutrophication there will be a great demand for oxygen by bacteria to decompose heavy loads of organic matter produced. Higher consumption rates of dissolved oxygen leads to oxygen deficient conditions, hypoxia or anoxia, in the water column.

Eastern coastal regions of the Arabian Sea are pumped with nutrient rich waters from intermediate depths due to upwelling in summer. Supply of nutrients makes these regions highly productive. Two other specific aspects responsible to aggravated oxygen deficiency in coastal waters are: firstly, source (upwelled) waters are already low in oxygen and secondly, prevalence of freshwater layer at the top results in strong surface stratification and therefore acts as a barrier layer for atmospheric oxygen diffusion or supply to coastal waters. Therefore, restricted replenishment from atmosphere makes the low oxygen but organic rich waters turn hypoxic (Figure 11). Such seasonal hypoxia, following the southwest monsoon upwelling, have been found along the west coast of India. The area covering oxygen levels <0.5 ml l^{-1} (or <25 µM) is estimated to be ~1.8x10^5 km^2 (Figure 17) where the upwelling intensity decreases from south to north (Naqvi *et al*., 2000). Time series observations in the last few years near Goa (see inset in Figure 17) have clearly documented the annual occurrence of hypoxia in September-October (Naqvi *et al*., 2006). Due to the poor availability of oxygen, bacteria utilize nitrate resulting in denitrification. Simultaneous occurrence of nitrification and denitrification in these coastal waters results in the build up of N_2O levels of ~500 nM, the highest ever recorded in seawater in the world oceans (Naqvi *et al*., 2000). Higher biological production during and following southwest monsoon could also be supported by the influx of atmospheric and river/ground water discharges of nitrogen released by human activities, primarily agriculture (Figure 18).

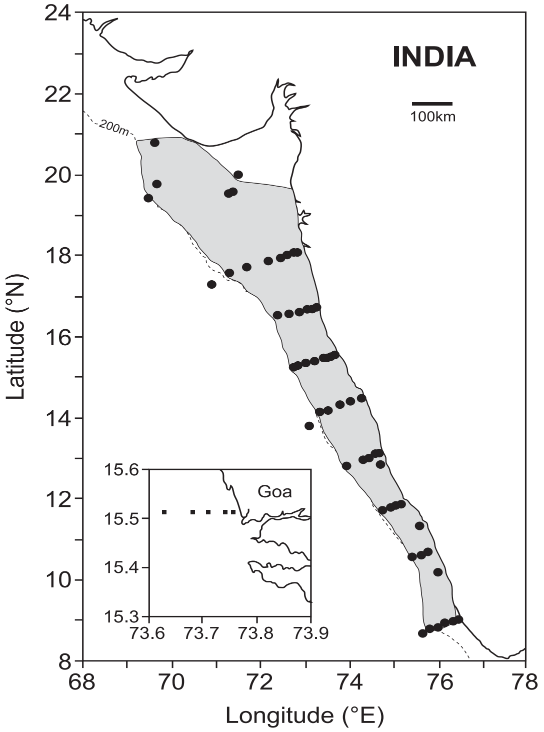

Figure 17. Shaded region along the west coast of India (of about 1.8 x10^5 km^2) experiences oxygen deficient (<0.5 ml l^{-1}) condition during the latter part and after the southwest monsoon (from Naqvi et al.*, 2000).*

3.13. *Is the North Indian Ocean a source or sink of biogenic greenhouse gases?*

The surface ocean is in continuous exchange with atmosphere. It is important to monitor air-sea fluxes of biogenically produced gases in order to understand their variability in view of climate change and possible alterations in the response of the ocean biogeochemistry. Exchange of a gas is determined by its diffusion rate across the air-sea interface. The magnitude of flux of a gas between air and seawater is determined by its concentration gradient between the two media and the exchange coefficient or piston velocity (primarily related to surface turbulence) of the gas in question. Gas exchange coefficients are determined from wind speeds (a parameter normally used to characterize surface turbulence). Biogeochemical processes, on the other hand, control the abundances of these gases in seawater and determine the direction of the flux. Therefore, the extent of air-sea fluxes of these gases depend both on the strength of wind systems and nature of biogeochemical cycles in a specified region, which might vary significantly from place to place and from time to time.

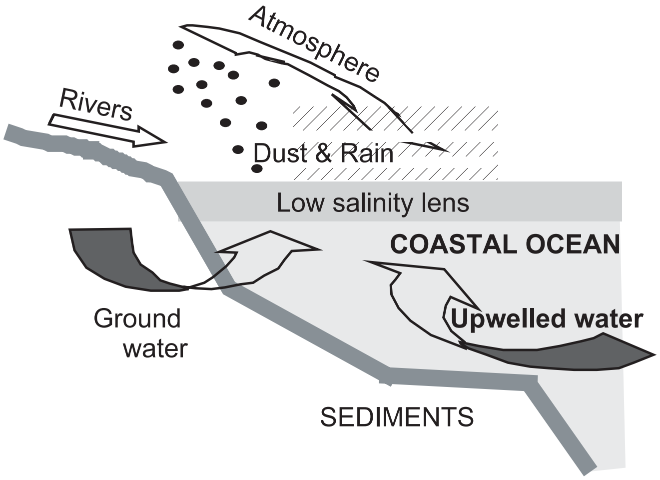

Figure. 18. Mechanisms of nutrient supply into coastal waters. Sometimes one or a few of these processes lead to eutrophication and subsequent development of oxygen deficient conditions. Agricultural fertilizer wastes can be discharged through river and ground water, and atmosphere.

The surface circulation, the biogeochemical processes and the resultant abundances of gases are quite different between the two North Indian Ocean basins. In the Arabian Sea intense vertical mixing occurs in both monsoons leading to very high biological production in surface waters and enrichment of these gases, in general. The entrainment in the Arabian Sea occurs through upwelling in summer and convection in winter (Figures 8 and 19). Therefore, the CO_2 concentrations are found to be nearly double to that in air in the core upwelling zones of the western (Kortzinger *et al*., 1997) and southeastern Arabian Sea (Sarma, 1998). Vertical exchange together with intense heterotrophic activities leads to CO_2 supersaturation in surface waters of the Arabian Sea (Sarma *et al*., 1998; Dutta, 2001). In contrast, prevalence of low salinity lens and weak winds at the surface in the Bay of Bengal reduces upward pumping of CO_2 (George *et al*., 1994) and N_2O (Naqvi *et al*., 1994), and therefore their surface concentrations are lower than in the Arabian Sea. The vertical diffusivity (Naqvi *et al*., 1994) in the Bay of Bengal (0.16 $cm^2\ s^{-1}$) is found to be one-third of that in the Arabian Sea (0.55 $cm^2\ s^{-1}$). Biological productivity triggered by river and atmospheric nutrient depositions, despite lower vertical exchange, makes the Bay of Bengal a seasonal sink for atmospheric CO_2 (Kumar *et al*., 1996). While the open ocean areas contained generally lower levels of gases coastal and upwelling areas experience anomalously higher abundances due to intense biogeochemical processes facilitated by air, water and land interactions. The highest concentrations of gases shown in Table 2 were found in coastal waters along the west coast of India during and immediately following the summer monsoon. Methane levels reaching about 13,000% (super) saturation are reported in estuarine waters of Goa (Jayakumar *et al*., 2001). The central and eastern Arabian Sea surface waters are found to serve as a source of atmospheric CH_4 (Patra *et al*., 1998). River and estuarine waters of Goa (Sarma *et al*., 2001), of Hooghly (Mukhopadhyay *et al*., 2002) and of Godavari (Bouillon *et al*., 2003) have been found to contain pCO_2 levels of 300-2500 µatm, 100-1500 µatm and 293-500 µatm, respectively. On the other hand, tidal mangroves of the Godavari delta region contained very high levels of pCO_2 of 1375-6437 µatm (Bouillon *et al*., 2003).

3.14. What is the contribution of North Indian Ocean to total gas emissions from South Asia?

As the information on gas abundances during extreme events is sparse in the northern Indian Ocean the errors associated with flux estimates could be significant and the actual emissions quite different. However, the values summarized here are qualitatively important as they reflect the different magnitudes at which the biogeochemical subsystems are operating in the North Indian Ocean basins. While the CO_2-supersaturated surface Arabian Sea perennially acts as a source (52-224 Tg C y^{-1}) of atmospheric gas the Bay of Bengal absorbs ~20 Tg C y^{-1}. Therefore, net CO_2 flows in opposite directions across the air-sea interface in the eastern and western parts of the North Indian Ocean. On the other hand, lower vertical diffusion in the Bay of Bengal leads

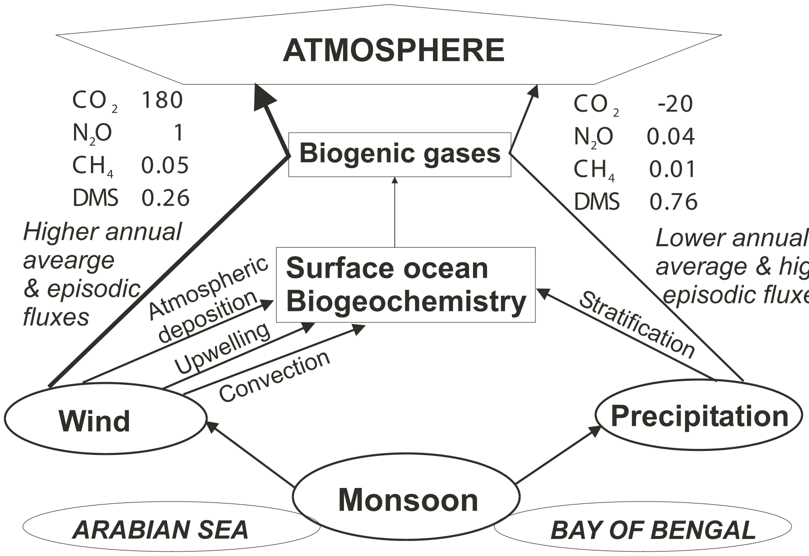

Figure 19. A schematic diagram depicting that monsoon associated physical processes in the surface ocean regulate the biogeochemical processes in the North Indian Ocean. The two basins (the Arabian Sea and the Bay of Bengal) of the North Indian Ocean experience different rates of vertical mixing. While the entrainment is efficient in the Arabian Sea (strong wind forcing) it is low in the Bay of Bengal because of stratification (caused by strong precipitation). Higher abundances of gases in the Arabian Sea, therefore, result in higher gas emissions than from the Bay of Bengal. The numbers shown against the considered gases indicate their average fluxes in (Tg y^{-1}) from the Arabian Sea (left side) and the Bay of Bengal (right side).

to lower emissions of other gases by several times, in comparison to those from the Arabian Sea. A comparison of these fluxes (listed in Figure 19) with the emissions from South Asia (Mitra *et al*., 2002) indicates that the North Indian Ocean contributes upto 22% of CO_2, 23% of S gases and negligible amount (<1%) of CH_4 but a substantial 82% of N_2O to the total atmospheric loadings from this region (Table 2).

Table 2. Abundances and sea-air fluxes of biogenic gases and contributions of North Indian Ocean to their emissions from South Asia.

Gas	Surface Abundance	Sea-to-air Flux[a] (Tg y^{-1})	Emission[b] from SA (Tg y^{-1})	Ocean contribution (%)
pCO_2 (matm)	200-700	32 - 204	715	4 - 22
N_2O (nM)	1-533	0.75 - 1.12	0.26	74 - 82
$(CH_3)_2S$ (nM)	0.1-525	0.13 - 1.3	4.3[c]	3 - 23
CH_4 (nM)	2-50	0.02 - 0.19	24	0.1 - 0.8

[a] pCO_2 range is the net after accounting for the Bay of Bengal as a sink

[b] Data obtained from Mitra *et al*. (2002)

[c] Data given in Mitra *et al*. (2002) for CH_4 emissions from India are extrapolated to South Asia (to an approximation based on CO_2 data)

4. BIOGEOCHEMISTRY AND SOCIETY

4.1. *Is Ocean biogeochemistry vulnerable to extreme natural events?*

Extreme events can be referred to as disturbances that cause sudden changes in forcing mechanisms of ocean biogeochemistry. Disturbances may occur in forms of cyclones and storms (atmospheric disturbances), tsunamis (created by submarine earthquakes) or local pollution (from industries), among others. Some of these disturbances substantially alter the biogeochemistry of the region. As the surface stratification reduces the upward nutrient supplies in the Bay of Bengal this short supply is overcome by frequent occurrence of atmospheric disturbances. The episodic churning due to these disturbances causes sudden cooling at the surface indicating that mixing with cold subsurface water has occurred (Sadhuram, 2004). Episodic mixing of surface water with that of nutrient rich subsurface waters appears to support biological production in the Bay of Bengal. The churning caused by the Orissa Super Cyclone in 1999 has been shown to enhance biological production several fold at a distance as far as off Chennai (Madhu *et al.*, 2002). On the other hand, satellite pictures have shown enhanced chlorophyll production in the eastern Indian Ocean triggered by the enormous churning caused by the Sumatra tsunami of 26 December 2004.

Besides promoting the surface production the natural disturbances also alter the rates of material transports at ocean-land and air-sea interfaces. The storms and cyclones cause massive transports of water and soils into the coastal ocean; the latter may also be carried into the deep sea in the form of turbidity flows or mud currents. Erosion and flushing of terrigenous materials (e.g. sand) to the sea during heavy discharge periods, including the monsoons, besides during catastrophic events is one aspect India has to carefully watch and study as this can have adverse effect on agro-economy and on the populace including their habitat.

Both the regular hypoxia along the Indian coastal waters of the Arabian Sea (Naqvi *et al.*, 2000) and frequent atmospheric turbulences over the Bay of Bengal (Murty *et al.*, 2000) are associated with the strong surface stratification caused by the low salinity lens (Figure 11). Anomalously high concentrations of N_2O (Naqvi *et al.*, 2000) and DMS (Shenoy, 2002) were found in oxygen deficient coastal waters of western India. Exceptionally higher levels of DMS (>500 nM) occurred along the west coast of India following upwelling driven plankton blooms. The emission of N_2O from this hypoxic region, only a fraction (~3%) of the Arabian Sea area and only in a period of 3-4 months, for instance, is equal to the annual average of the entire Arabian Sea (Naqvi *et al.*, 2000). In the Bay of Bengal, episodic fluxes of DMS were found during highly turbulent conditions over the Bay of Bengal, e.g., during a deep depression in 1999, at the maximal rate of 41 µmol S m^{-2} d^{-1} (the highest known for the world oceans, Shenoy, 2002). Over the equatorial Indian Ocean seven times more flux occurred in winter 1999 than that in the previous year due to a turbulent event associated with the TCZ (Shenoy *et al.*, 2002). Such episodic emissions of gases between air and sea, of the duration of only a few days, may at times equal or exceed the annual average fluxes.

4.2. *Are hypoxia and harmful algal blooms related?*

Intense denitrification in waters along the west coast of India can make nitrate a limiting factor in phytoplankton production. As the regenerated phosphate is already available in the water column nitrogen fixing plankton begin to appear. It has been common to find nitrogen-fixing plankton such as *Trichodesmium* or *Noctiluca* in blooms in inshore and offshore waters of the North Indian Ocean (Naqvi *et al.*, 1998; Sahayak *et al.*, 2005; references therein) but the extent, reasons and mechanisms of their emergence are poorly known. The blooms appear as red patches on the sea surface and hence are called as 'red tides' (Figure 20). Non-availability of nitrate in surface waters either due to strong surface stratification or to intense microbial activity, leads to the absorption of atmospheric nitrogen to support primary production. Fish death in and around regions of plankton blooms is a frequent phenomenon (e.g. Naqvi *et al.*, 1998). The fish death is caused either by toxic (poisonous) substances released or clogging of gills by the blooming organisms. Clogging of gills blocks the respiration routine making the fish suffer from asphyxiation. Hence, these blooms are referred to as harmful algal blooms (HAB).

The occurrence of harmful algal blooms is receiving worldwide attention in view of their adverse impact on human health and ecosystems in coastal regions, and climatic significance. For instance, a stench has been found in September 2004 along the southwest coast of Kerala due to the proliferation of the tentatively identified *holococcolithophore* blooms (Ramaiah *et al*., 2005). Following the blooms the coastal population suffered from severe nausea, headache, vomiting sensation etc. either because of the consumption of infected fish or inhalation of toxic gases produced by the bloom associated processes. Therefore, it is important to keep a close watch on the occurrence of such blooms in order to prevent coastal human health hazards and maintain ecological balance.

Figure 20. Decay phase of a Trichodesmium *bloom in Andaman Seas occurred in 1997 (Courtesy Dr. V. P. Devassy). (See inside back cover for colour image).*

4.3. *Is the Indian Ocean biogeochemistry sensitive to bioinvasion?*

Establishment of a population of organisms, plant or animal, alien to native locations (e.g., our tropical Indian Ocean) is referred to as bioinvasion. Such occurrences are an important aspect of the biogeochemical processes since the spreading and proliferation of alien organisms might alter the biological sequences and ecological balance in the region. Introduction of new species may occur through transportation by surface circulation in the ocean (natural), by ballast water in ships or deliberate introduction by human activities. The most striking example of bioinvasion is the occurrences of *Phaeocystis pouchetti* in the central parts of the tropical Arabian Sea during the southwest monsoon of 1996 (Madhupratap *et al*., 2000). The *Phaeocystis* occurs mostly in coastal regions of temperate and Polar Regions of the world oceans. Thick blooms of *Phaeocystis* were found in summer of 1996 during an Indian expedition to the Arabian Sea as a part of the Joint Global Ocean Flux Study (JGOFS-India) project. These blooms have been marked by thick mucous materials that clogged plankton nets during sampling. The mucous, secreted by *Phaeocystis*, is a sticky polysaccharide material and therefore could be found sinking to subsurface layers (~600 m) in the form of large transparent exopolymer particles (Kumar *et al*., 1998). Production of blooms with a large quantity of mucous materials might adversely affect the biological structure of the region.

The proliferation of the supposed *holococcolithophore* bloom off Kerala coast (as mentioned in the last part of the above section) again appears to be another example of bioinvasion (Ramaiah *et al*., 2005). While the coastal population suffered from ill effects of this bloom and the associated gases released, the climatic significance of the latter is unknown. Following this stench intense blooms of *Noctiluca* have been found to occur in the affected region (Sahayak *et al*., 2005)

Enhanced biological production in coastal waters due to naturally driven upwelling is beneficial to the growth and economy of the local populations. However, some ecological damage is inevitable if such high production turns into eutrophication or into the proliferation of native (*Trichodesmium* or *Noctiluca*) or alien (*Phaeocystis* or *holococcolithophore*) species. Over 18 species of marine plants/animals are identified to have invaded the coastal waters of India (Anil et al., 2002). The damage occurs through deliberate killing of other organisms in water, such as fish, and release of biogenic gases or toxic substances into water and air.

4.4. *Is ocean biogeochemistry socially relevant?*

The ocean biogeochemistry is closely linked to our everyday life in several ways. The most obvious in short time scales is the marine food resources on which coastal population survive. Among the long term benefits, buffering of atmospheric gases by the ocean enables the Earth sustain habitable climatic conditions. Besides these, the humans directly extract enormous quantities of non-living resources that result from ocean biogeochemical processes. These are oil, natural gas and minerals deposits from sediments. The oil and natural gas industry from continental margins is one of the biggest industries in the world. The minerals of future importance are marine ferro-manganese deposits, cobalt-crusts, phosphorite, carbonate deposits etc.

The ocean biogeochemical components also maintain records of events of global and environmental change in the past. Since the materials settle at the bottom as a function of time, analyses of stable isotopes of oxygen, carbon and nitrogen along with other geochemical constituents or proxies yield information on changes in the Earth climatic conditions (such as ice ages) and the consequent ocean biogeochemistry. Recent human interference on climate and the changes in surface ocean biogeochemistry in certain regions will be recorded in corals and coastal sediments. Formation of layers (monsoon and non-monsoon bands) in some corals (*Porites*) enables the construction of changes in regional climate and surface circulation processes over annual to centennial scales. Changes in climatic conditions will be identified through variations in fractionation of stable isotopes of oxygen (16 and 18) and carbon (12 and 13) and productivity through variations in metals such as Cd, Ba, etc. These marine stratigraphic (chronological) records are of paramount importance to understand the climatic changes and the associated oceanic processes, natural or anthropogenically driven, so as to maintain a balance among sustainable development, health of ecosystems and habitable climate.

5. A FEW OUTSTANDING ISSUES FOR FURTHER RESEARCH

The following are a few issues of immediate concern for better understanding of the biogeochemistry of the North Indian Ocean and its significance:

a. Variability in biogeochemical processes and properties in time and space
b. Factors determining biological productivity and the extent of its variability
c. Variability in biological diversity and biological succession in time and space
d. Modifications to biogeochemical processes and feedbacks due to human interference
e. Transfer and transformation of materials involved in biogeochemical cycles
f. Differences in water column denitrification between the east and west basins
g. Role of metals in biological productivity
h. Nature and fate of dissolved organic matter
i. Relative significance of nutrient supply from atmosphere, rivers and ground waters (including fertilizer leaks) to coastal productivity
j. Sediment- water exchange influence on nitrogen cycling and budgets
k. Role of continental margin sediments in coastal biogeochemical cycles
l. Exchanges of gas, liquid and solid materials during extreme events
m. Occurrence of hypoxia in areas other than eastern Arabian Sea
n. Monsoons – hypoxia – (harmful) algal bloom connections
o. Material exchanges across marine boundaries.
p. Functioning of major estuaries and special ecosystems (e.g. Sunderbans) processes .

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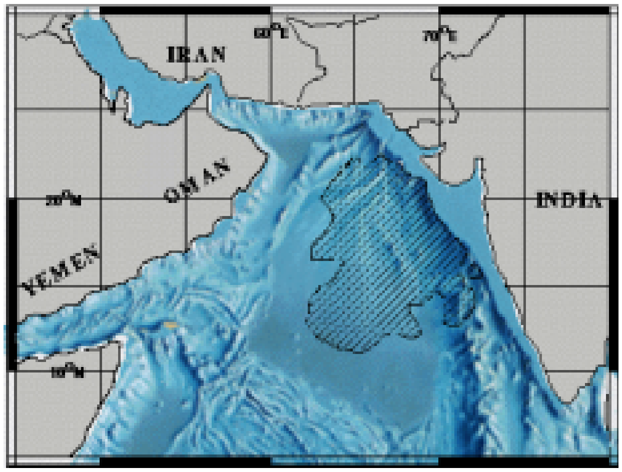

Figure 14. Shaded area indicates the region of active water column denitrification in the central and eastern parts of the Arabian Sea (after Naqvi, 1991).

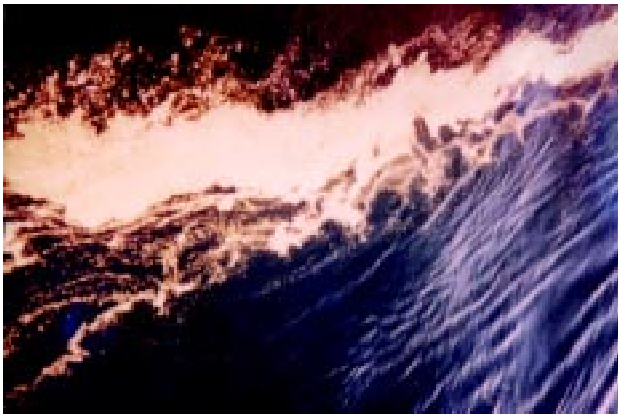

Figure 20. Decay phase of a Trichodesmium *bloom in Andaman Seas occurred in 1997 (Courtesy Dr. V. P. Devassy).*