



AIR-SEA EXCHANGES OF MATERIALS IN THE INDIAN OCEAN REGION: CONCERNS AND STRATEGIES

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Exchanges of materials at the air-sea interface are linked to earth's heat budget and the natural balance is being increasingly affected by human activities. Three major issues of national concern with respect to changes in oceanic and atmospheric conditions are presented. These are: occurrence of oxygen deficient conditions along the Indian coast and their relation to use of fertilizers, effect of anthropogenic pollutants on south Indian Ocean atmosphere and impact of inter-linking of rivers on the coastal ecosystems.

Introduction

Human interference with the climate has been on unabated increase since the middle of the 19th century due to rapid industrialization and civilization. The growing demands of changing life styles culminating in large scale deforestation and excessive burning of fossil fuels are the oft cited reasons for the ever increasing accumulation of greenhouse gases in the atmosphere. The carbon dioxide (CO₂), which is estimated to have swelled by 150 giga tons during the last 150 years with its present abundance of 371 ppmv (parts per million by volume), is ranked as the major culprit causing global warming. The last century witnessed a clear rise of 0.6-0.8°C in the atmospheric temperature which is sufficient to have caused changes in regional climates and melting of ice. While greenhouse gases such as water vapour and CO₂ helped maintain warm temperatures required for production and sustenance of life on earth, excessive of these gases prove destructive to life creating imbalances in rainfall and other natural processes.

The atmospheric temperature fluctuated widely during the past geological periods with several of the warmer events - interglacial periods - of the past unrelated to human actions. Gases trapped in Vostok ice cores of Antarctica recorded changes in CO₂ and methane (CH₄) abundances with time during the last ~ 400,000 years. The atmospheric CO₂ varied during these periods between 180 ppmv and 280 ppmv; the highest value being far less than the current level of 371 ppmv, demonstrating clearly the effects of anthropogenic emissions of the recent past. The Vostok data set could establish a direct correlation between the temperature and greenhouse gases, but it predicts higher values of atmospheric temperature based on the current levels of CO₂ and CH₄ concentrations (Kirchner, 2002). Yet the mutual dependence of atmospheric temperature and concentrations of greenhouse gases is qualitatively undisputable.

Air-sea exchange of greenhouse gases and aerosols

Oceans have the capacity to modulate greenhouse gases in atmosphere, and in their absence the concentrations of these gases in air would have been more alarming. Of the

estimated ~7.4 giga tons per year of CO₂ emitted anthropogenically the global ocean absorbs about 2 giga tons, by way of gas exchange across the air-sea interface, while 3.4 giga tons carbon accumulates in air. The remaining *missing* carbon of 2 giga tons is probably being fixed by biota on land in an unknown location, coniferous forests in temperate regions being the most probable sites. The dissolved total CO₂ concentration in seawater (~2000 μM) works out to be ~150 times that in atmosphere (13μM). It is present largely as bicarbonate ion and can easily be converted to gaseous CO₂ with minor reduction in pH. The gaseous CO₂ in seawater determines the extent of air-sea exchange. But small changes in temperature or pH can modify gaseous CO₂ content in seawater. Thus shifts in physico-chemical and biological regimes in *the* surface ocean have a role in controlling the air-sea exchange of biogenic gases.

The ocean surface also produces aerosols, the particles flying in air, which are carried over long distances by wind. Turbulence at the air-sea interface is the major cause for breaking of the bubbles and release of sea-salt aerosols and gases to atmosphere. A class of aerosols known as *non-sea-salt* (nss) aerosols is produced from reactions/condensation of gases or vapour released into the atmosphere. An excellent example of this class is dimethylsulphide (DMS, [(CH₃)₂S]) gas, which is produced through intricate biochemical processes in the surface ocean, and converted to nss-sulphate aerosol in the atmosphere and finally to small particles known as condensation nuclei (CN). At the top of the atmosphere the CN in clouds reflect incoming solar radiation and help in indirect global cooling. On the other hand, aerosols carried from land may be transformed over the ocean causing alterations in physico-chemical and biogeochemical properties of air and surface ocean.

The North Indian Ocean scenario

The North Indian Ocean is a source of atmospheric gases although its northeast component acts seasonally as a sink of CO₂ in air (Table 1). While the Arabian Sea, the northwest component, perennially emits on the average ~180 mega tons of CO₂ per year, the bay absorbs about 20 mega tons per year. The super-saturation of CO₂ in the Arabian Sea surface waters is attributed to intense biological activity including the zooplankton grazing. On the other hand, the freshwater flux, which is substantial and estimated at 1.6 Km³ per year from the sub-continental rivers, produces a low salinity layer (LSL) in the months following southwest monsoon rains in the Bay of Bengal. The resulting stratification limits vertical mixing of surface and subsurface waters in the Bay of Bengal and the CO₂ lost to air or fixed photosynthetically in the thin surface layer is not replenished through supply from upward pumping. The surface bay, which is thus largely under-saturated, absorbs atmospheric CO₂.

Despite the contrasting emission behaviour of CO₂ these two northern arms of the Indian Ocean emit continuously nitrous oxide (N₂O), CH₄ and DMS, although the rate of emission of N₂O from the Bay of Bengal is only one-third of the Arabian Sea. The differential rates of emission of N₂O are due to differences in the vertical diffusion (Naqvi et al., 1994), which is lower in the Bay of Bengal (0.16 cm² s⁻¹) than in the latter (0.55 cm² s⁻¹). The DMS fluxes are comparatively higher from the Bay of Bengal although its abundance

Table 1: Emissions (positive) of biogenic gases (in 10^6 tons y^{-1}) from the North Indian Ocean and their contributions to total regional atmospheric loading

Gas	Carbon dioxide	Nitrous Oxide	Methane	Dimethyl sulphide
Arabian Sea	180 ^a	1 ^b	0.1 ^c	0.26 ^d
B. of Bengal	- 20 ^a	0.03 ^b	Not known	0.78 ^d
North IO	160	1.03	0.1	1.04
Anthro ogen. ^c	715	0.26	24	4.2 (as SO ₂)
% NIO loading	20	74	0.4	20

^afrom Kumar et al. (1996) and Kumar and Shenoy (2004)

^bfrom Naqvi et al. (1994, 2000) ^cfrom Jayakumar et al. (2001)

^dfrom Shenoy (2002) and Kumar and Shenoy (2004) ^efrom Mitra et al. (2002)

is only about one-third than in the Arabian Sea (mean: 5.5 nM) surface waters (Shenoy, 2002). Carbon dioxide and DMS releases from the North Indian Ocean alone contribute to 20% of the total emissions of carbon and sulphur gases from the South Asia (Kumar and Shenoy, 2004). While CH₄ emission does not seem to be significant the seas around India contribute three-times more N₂O to atmospheric burden than by anthropogenic activities in South Asia (Table 1).

The concern

The climate over the Indian Ocean and the adjacent continents is one of the most active systems in the world responsible for regular annual occurrence of monsoons in the region. The main stay of population of this region is agriculture which is sustained largely by the monsoon rainfall, the southwest monsoon being the stronger. The intensity of monsoon of the Indian Ocean region is dependent not only on the ocean-atmosphere interactions of the region, but remote physical processes taking place elsewhere, such as the El Nino-Southern Oscillation (ENSO) in the Pacific Ocean. Another important feature connected to monsoon rainfall is the Indian Ocean Dipole, an Indian Ocean equivalent of the El Nino. Besides, many low pressure systems develop over the Bay of Bengal whenever the sea surface temperatures crosses the 28°C mark. The Bay of Bengal interestingly receives freshwater from the rivers of the subcontinent which results in a strong thermohaline stratification that facilitates development of such low pressure systems. The Arabian Sea, receiving less freshwater supply, naturally is less conducive for low pressure systems. As the global warming can modify regional climates and monsoons, the increasing release of CO₂, and other gases and aerosols from this region is of immediate concern to India.

Ocean-atmosphere interactions and the climate

The rainfall is linked to sea surface heating through equations of physics, but the ocean biogeochemistry plays a key role in determining the atmospheric chemical composition and thus the radiation budget. The biological pump in the ocean steadily removes atmospheric CO₂ and transports the particulate carbon to the deep sea. The biological activity can alter pH, which is the master variable to control CO₂ speciation, and thus the oceans exert a major control on atmospheric CO₂ abundance. Other important, but not of equal potential,

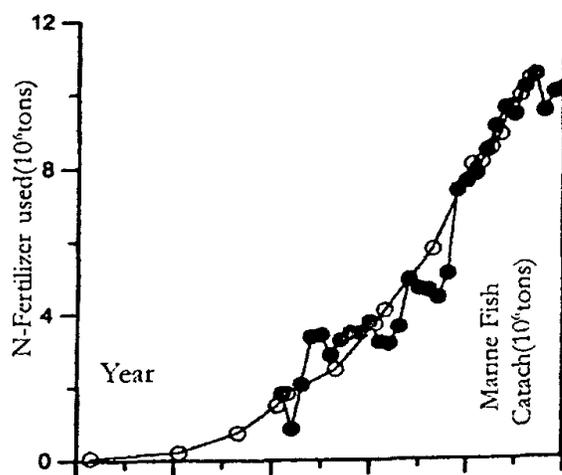


Fig. 1. Increases in nitrogen fertilizers used and marine fisheries production in India in the last few decades (data from Agarwal and Narain, 1999; FAO, 1981, 1990, 2002).

links between the oceans and climate are the phytoplankton and gases of sulphur. The phytoplankton pigments absorb solar radiation and cause a rise in sea surface temperature. Sulphur gases emitted from anthropogenic and natural sources can lower the atmospheric temperature that can potentially counter warming within clouds caused by carbon soot released from inefficient fuel burning. Although contentious at present speculations on the impact of aerosols on local hydrography are ripe (Srinivasan and Gadgil, 2002; Ramanathan et al., 2002). Therefore, under the present global change scenario, alterations occurring in natural processes need to be understood holistically in order to prevent adverse consequences to life in the centuries ahead.

Issues of national concern

Most of the human demands lead to direct or indirect interference with the environment. Three examples are cited here.

Green revolution: To meet the growing demands for wheat and rice to feed the country's population, India had to go in for green revolution during the past few decades through intensive farming by bringing large areas under cultivation and encouraging the farmers to adopt improvised practices including the use of chemical manures. Thus nitrogen fertilizers utilization in India has exponentially increased from a modest figure of 0.06 mega tons in 1950s to more than 10 mega tons per year in the second half of the last decade (Fig. 1) to boost food grain production. It is indeed a proud achievement to make the country self-reliant in food production, but it was not achieved without a cost. First, large areas of natural habitats are converted to arable land. Second, fertilizers used in agriculture are not fully consumed with remnants accumulating in ground waters, or undergoing microbially mediated processes such as denitrification. Nitrate accumulation in ground waters make people susceptible to *blue baby* disease.

Nitrate fertilizers sprayed in fields enter the coastal waters as agricultural effluents via the atmosphere (dust and rain), ground water and river water discharges (Fig. 2). On the positive side, the discharged fertilizers are expected to enhance biological productivity leading to higher fish production. Fig. 1 shows the positive correlation between fertilizers used

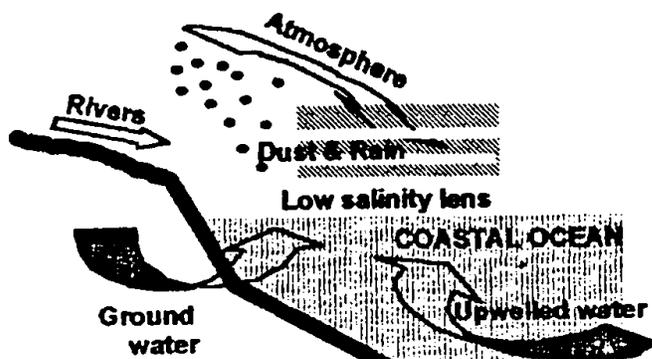


Fig. 2. Mechanisms of nutrient inputs into coastal waters leading to Eutrophication and oxygen deficient conditions.

and the marine fish catch. The fish yield increased from 1.16 mega tons in 1971 to 2.8 mega tons in 2000 in the Indian coastal waters (FAO, 1981,1990,2002). Despite the evidence provided in Fig. 1, it is difficult to conclude that the increase in marine biological production is entirely due to leakage of agricultural effluents into coastal waters, as the present knowledge on the seasonal variability of nutrients and biological production in waters along the Indian coast is still limited. If this theory is valid and even if a part of the increased biological activity is due to fertilizers it can produce higher amounts of greenhouse gases. The leaked fertilizers are considered to be intensifying the coastal eutrophication over the past few years. The increase in organic matter formed in coastal waters creates oxygen deficient conditions and accumulation of NO along the west coast (Naqvi et al., 2000). The measured levels of N_2O reached a maximum of 533 nM being much higher than normal levels of (30 n f in the upper 30 m in open Arabian Sea waters. This, in turn, has been resulting in abnormal higher sea-to-air fluxes. An area of just $0.18 \times 10^6 \text{ km}^2$ experiencing anoxia along the western continental shelf of India has produced 0.39 mega tons of N_2O in a mere six months, which is equivalent to the annual emission under normal conditions from entire Arabian Sea of $6.23 \times 10^6 \text{ km}^2$ (Naqvi et al., 2000).

However, it should be thoroughly explored if the occurrence of anoxia and N_2O build up in coastal waters of western India can alternatively be triggered naturally, before ascribing it to the use of chemical fertilizers. When winds blow parallel to the coast during the southwest monsoon, the nutrient laden (e.g. $10 \mu\text{M}$ of nitrate) subsurface Arabian Sea waters are transported into the coastal regime (Fig. 2) due to upwelling. When nutrients are available aplenty, production and respiratory activities are intensified due to eutrophication. During the same time fresh water discharged spreads as a thin (some times less than 5 m thick mixed layer) LSL in the coastal ocean preventing the oxygen supply into waters at depth (Naik, 2003). Accumulation of organic matter over the time leads to near complete consumption of oxygen in the subsurface waters due to enhanced bacterial respiration. Under these conditions, the available nitrate is used as an oxidant and at times it is totally depicted in the subsurface waters. Simultaneous occurrence of nitrification and denitrification processes produce large quantities of N_2O in the oxygen depleted coastal ecosystems, which act as periodic chimneys (Naqvi et al., 2000).

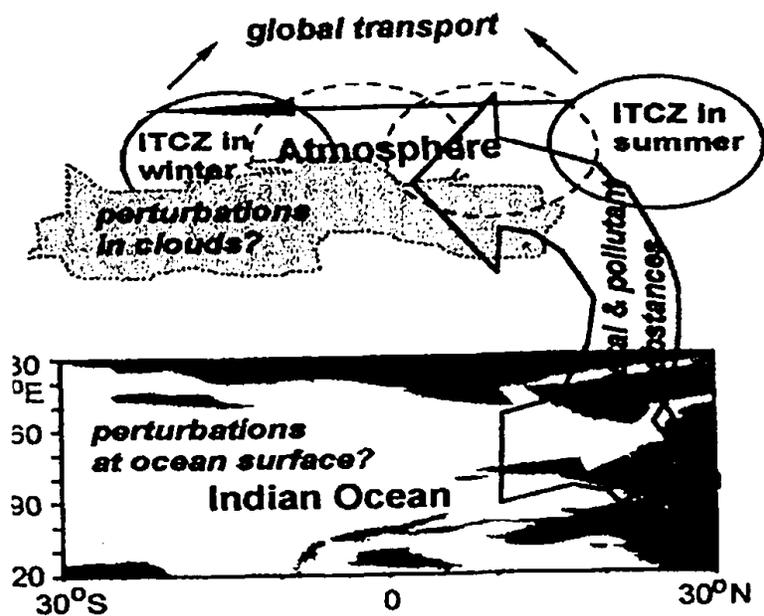


Fig. 3. Schematic depiction of transport pathways of aerosols from land and ocean to atmosphere and possible modification of atmospheric and surface ocean processes.

Fuels: Substantial percentage of population of South Asia, lives in rural areas which still adopts the traditional means of burning firewood and dung cakes for cooking. Due to their inefficient combustion these fuel materials produce aerosols including nss-sulphate and black carbon, which are transported to higher altitudes and longer distances (Mitra et al., 2002). Recent Indian Ocean Experiment (INDOEX) showed the presence of a large haze consisting of anthropogenic aerosols over the South Indian Ocean (Ramanathan et al., 2001). During the north east monsoon, the Inter Tropical Convergence Zone (ITCZ) - the latitude belt where air masses from northern and southern hemispheres converge - is located south of equator as the cold and dry winds blow from north (South Asia) to south (Indian Ocean). The winds from landmasses carry aerosols of natural and anthropogenic origin. The human induced aerosols are dominantly nss-sulphate and black carbon, and their percentage of the total aerosol content is an indicator of the magnitude of human interference with the purity of the regional atmosphere. The sulphate aerosols are converted to CN and hence human interference with respect to atmospheric sulphur is reducing the extent of global warming. However, the presence of black carbon in the atmosphere traps the heat, thereby warming the clouds and delaying the precipitation (Satheesh and Ramanathan, 1999). If true, the delay/reduction in moisture condensation will have a negative effect on regional rainfall and hydrological cycle. Alternatively, condensation or adsorption of water molecules on to soot particle surface may make the aerosol surface act like a mirror and reflect the radiation. The dominant mechanism is yet to be investigated. Both the possibilities, however, will lead to a reduction in the radiation (how significant?) reaching the sea/land surface. The resultant low temperatures at the surface will not only affect gas abundance and exchange processes, but also alter the rates of biological processes. Changes in these processes will influence feedbacks between ocean and atmosphere.

Inter-linking of rivers: The most widely discussed project in the recent times is the inter-linking of rivers to divert waters from surplus basins to those deficient in water. The ecological implications of the project are numerous. The vegetative cover on land will increase and influence regional climates. An excellent example is that of Godavari basin, which exhibits a reduction in temperature during the day (0.2-0.7°C) and its increase during the night (0.5-0.6°C) due to increase in vegetation between 1970 and 1998 (Sarma et al., 2001). The basin also witnessed a substantial reduction in the number and intensity of famine events during the period as a result of the basin climate becoming wetter (Sarma et al., 2001). Such changes would benefit the local population, besides limiting soil erosion. Such positive changes can occur in many parts of the country following the inter-linking of rivers. However, the reduced river discharges and the regional atmospheric dust depositions as a consequence of river linking will modify the coastal biogeochemical systems and regional greenhouse gas inventories. For instance, the mangrove ecosystems in South India are found to emit three times CH₄ under anthropogenic influence than under natural (7 mg m⁻² hr⁻¹) conditions (Purvaja and Ramesh, 2001). The coastal wetland systems will be modified when water flows are *diverted* through *connected* rivers and changed discharge points.

The strategies

While the development and comfortable living have to go together, it is important to see that the ecological balance of environment is sustained and monitored. Any environmental changes can be detected only if the secular variations of ecological properties are studied through long-term records and quantified. Such records shall enable one to decipher, deviations from natural variability in the atmosphere and neighbouring oceans. Thus stations need to be set up for continuous monitoring of environmental properties at key locations in land, coastal and open sea regions. The records obtained help us resolve variations in properties due to local and remote forcings or to human influence. The sharing of these results with the policy makers will facilitate safeguarding the regional environment and reduce human impact on climate.

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