

The Indian Ocean—An Environmental Overview

R. SEN GUPTA* & S.Z. QASIM**

During the International Indian Ocean Expedition (IIOE), 1962-65, the Indian Ocean was defined as the area between 25°N and 40°S latitudes and 45°E and 115°E longitudes. This region included all the straits, adjacent seas and semi-enclosed basins within the littoral countries, which, because of their special characteristics, form a subject matter of a separate communication.

In the present review the Indian Ocean has been defined as the area between 25°N and 30°S latitudes and between 40°E and 98°E longitudes. This has been done simply because of the availability of data with us on different aspects of oceanography which have been discussed below. Geographically, it is the area from 30°S latitude to the Gulf of Oman and the head of the Bay of Bengal on the north and from the East African coast on the west to the coastlines of Burma, Thailand and Malaysia (excluding the Strait of Malacca) on the east (Figure 1).

In this region of the Indian Ocean, there are altogether 19 countries. Their total area is about $9.6 \times 10^6 \text{ km}^2$ and they are inhabited by about 1221 million people. The average population density is $127/\text{km}^2$. Thus, on an average 22.5% of the world population lives in 18.6% of the total land area.

* Dr. R. Sen Gupta is a senior scientist at the National Institute of Oceanography, Dona Paula, Goa.

** Dr. S.Z. Qasim is the Secretary, Department of Ocean Development, Govt. of India Mahasagar Bhavan, New Delhi and responsible for recent up surge in the Oceanographic researches in India and has led the First Indian Expedition to Antarctica.

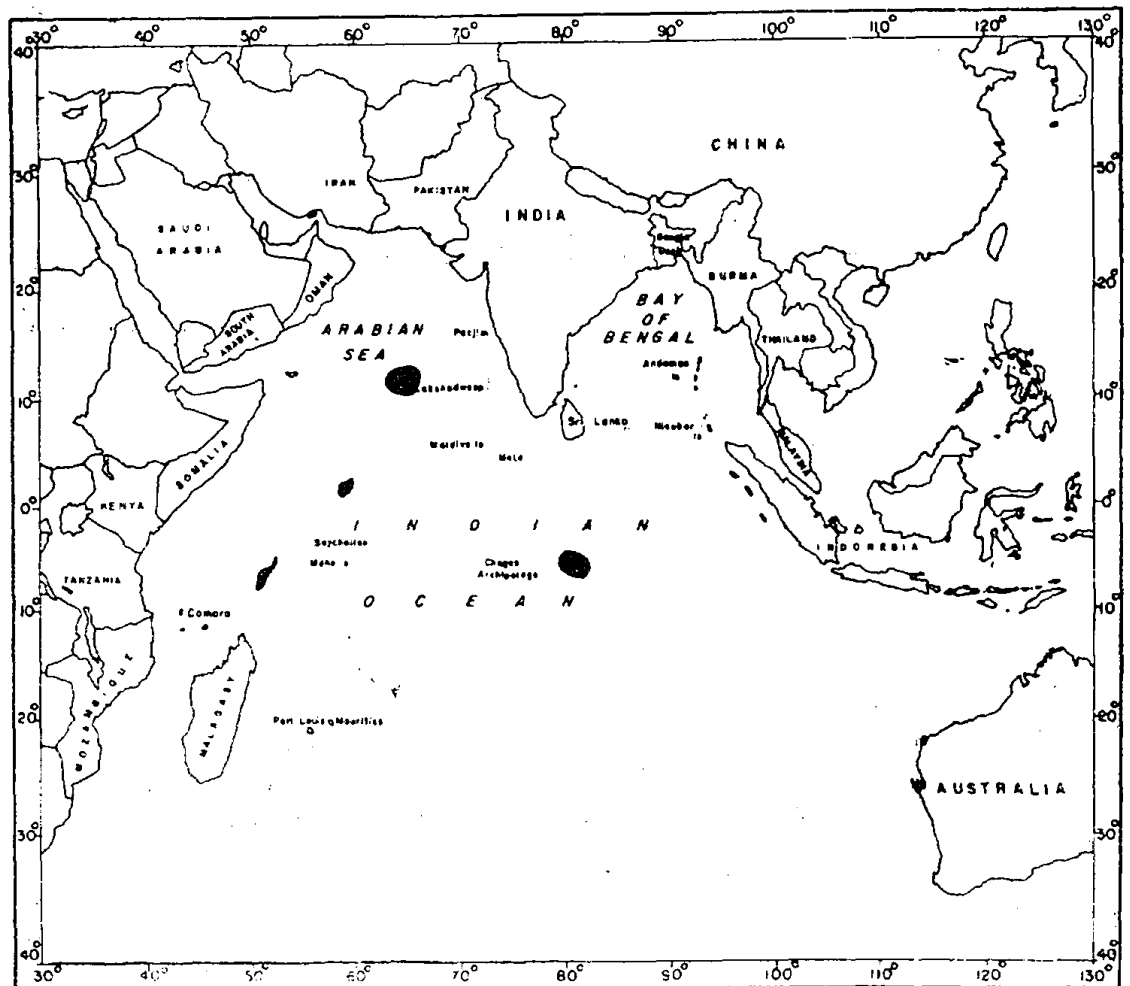


Fig. 1.

Oceanographic Features

From the data collected during the IIOE a comprehensive atlas of physical and chemical features has been published by Wyrski (1971). The various characteristics can, briefly, be summarized as follows :

(a) Physical

The Indian Ocean occupies an area of $74.92 \times 10^6 \text{ km}^2$ including the marginal seas (Dietrich, 1963). Its average depth is 3873 m. Areawise, the Indian Ocean is 20.8% of the total world oceans. According to Budyko (1972), the Indian Ocean is an area of negative water balance. Annually it receives 6000 km^3 of river runoff and $88,000 \text{ km}^3$ of precipitation while its evaporation is $103,000 \text{ km}^3$.

However, there are some parts of the Indian Ocean in which the water balance is positive. One such area is the Bay of Bengal which forms the northwestern part of the Indian Ocean. The Bay occupies an area of $4.087 \times 10^6 \text{ km}^2$ between latitudes 0° — 25°N and longitudes 80° — 100°E (Qasim, 1977). It receives annually a precipitation of $11,000 \text{ km}^3$ and a runoff of 1730 km^3 . It has been calculated that these volumes of precipitation and runoff, assuming the limit of dilution only upto 25 m depth, would dilute the surface water by about 5% (Sen Gupta *et al.*, 1978a).

The Arabian Sea, forming the northwestern part of the Indian Ocean is, however, a region of negative water balance. It occupies an area of $6.225 \times 10^6 \text{ km}^2$, between latitudes 0° and 25°N and longitudes 50° and 80°E (Qasim, 1977). It receives annually a precipitation of $10,000 \text{ km}^3$ and runoff of 525 km^3 from the rivers of India and Pakistan. Thus, these two areas, although cover only about 13.8% of the total area of the Indian Ocean, receive 37.6% and 23.9% of total precipitation and runoff, respectively. In fact, the Bay of Bengal and the Arabian Sea together occupy only 3% of the world oceanic area but receives 9% of the global river runoff.

The northern boundary of the Indian Ocean is landlocked and it receives waters of high salinity from the Gulf and the Red Sea. The Gulf water flows through the Hormuz Strait which has a maximum sill-depth of about 100 m (Duing and Schwill, 1967) while the Red Sea water flows through the Strait of Bab-el-Mandab with a maximum sill-depth of 125 m. These are the only two water masses of

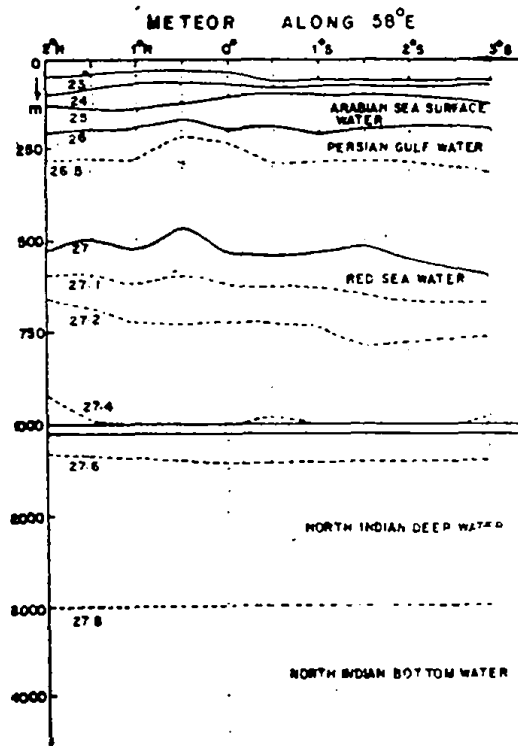


Fig. 2

Fig. 2.

the Indian Ocean which originates from the north. The presence of the Gulf and the Red Sea water masses have been traced all over the Arabian Sea upto the equator and into the western part of the Bay of Bengal. The Gulf water can be identified in the depth range 100 to 300 m of the Arabian Sea. It can also be traced upto about 500 m depth in the equatorial Indian Ocean with a characteristic sigma-t of 26.5 (Figure 2). The water from the Red Sea can be traced by its characteristic sigma-t of 27.1 between 400 and 900 m depth in the Arabian Sea and to about 1000 m depth in the equatorial Indian Ocean (Rochford, 1964; Wooster *et al.*, 1967). Apart from these, two other surface water masses are formed in the Northern Indian Ocean. These include a high salinity surface water in the northern and central Arabian Sea formed due to excess of evaporation there and this water mass is present upto a depth of about 125 m. It has a sigma-t of 25 (Rochford, 1964). Due to an excess of precipitation and a very large volume of runoff, low salinity surface water is formed in the Bay of Bengal. This water mass flows south of Sri Lanka to the west and can be traced over a considerable distance into the Arabian Sea (Wyrtki, 1973).

Ivanenkov and Gubin (1960) termed the water mass between 100 and 300 m as the North Indian Ocean Deep Water with a sigma-t of 27.6; and the water mass below 3000 m with a sigma-t 27.8 as the North Indian Ocean Bottom Water (Figure 2). These two water masses are formed as a result of mixing of the Antarctic Deep and Circumpolar water masses with low temperature and low salinity flowing northward. According to Wooster, Schaefer and Robinson (1967) water masses in the Northern Indian Ocean below 1000 m depth originate in the Antarctic circumpolar region and enter the Northern Indian Ocean from the southwest. These water masses penetrate northward and spread out in both central and eastern basins and can be identified by their characteristic sigma-t values. In addition to the water masses, broadly classified above, there are several other types of water masses formed due to mixing, which have not been described here due to limitation in space.

One of the unique features of the Indian Ocean is that in its northern region the surface circulation reverses every half year, from northeast during the winter monsoon to southwest during the summer monsoon. This phenomenon makes the Indian Ocean a very suitable area to study the ocean-atmosphere interaction.

In relation to the equator the Indian Ocean has an asymmetric shape largely due to the presence of the Asian continent. The result is that this ocean gets separated from the deep-reaching vertical convection areas of the northern hemisphere. In addition it gets influenced upto 10°S by the characteristic atmospheric circulation, known as the monsoon circulation (Dietrich, 1973). Such an asymmetric configuration leads to a weak circulation and poor renewal at depths of the northern Indian Ocean and the reversal of the surface circulation with the two monsoons.

Wyrtki (1973) has identified three distinct large scale circulation systems in the Indian Ocean, namely, (i) the seasonally changing monsoon gyre north of 10°S; (ii) the southern hemispheric subtropical anticyclonic gyre; and (iii) the Antarctic waters with the circumpolar current.

During the northeast monsoon (November-April) the oceanic circulation, north of the equator, remains moderately strong and follows direction east to west. It penetrates a depth lower than the thermocline. Due to the shoaling of the thermocline, a weak upwelling has been identified in the northeastern part of the Indian Ocean. The northeast monsoon is quite strong in the Bay of Bengal, in which enormous volume of river runoff probably compensates the weak upwelling of the northeastern region.

During the southwest monsoon, the South Equatorial current becomes stronger. This current subsequently forms the East African Coastal Current and flows northwards ending up as the Somali Current, which frequently attains a velocity as strong as the other western boundary currents, e.g. Gulf Stream or the Kuroshio (Warren *et al.*, 1966). The monsoon current, the South-Equatorial current and the Somali current forms a strong wind-driven gyre in the equatorial Indian Ocean (Wyrtki, 1973). This gyre then breaks down in a series of large gyres in the Arabian Sea (Duing, 1970). The resultant upwelling along the Somali coast is most intense between 5°N and 11°N, where the entire warm surface layer is removed and the subsurface water with temperatures well below 20°C reaches the sea surface (Warren *et al.*, 1966).

Strong winds blow also parallel to the Arabian Coast, east of 55°E during the southwest monsoon and cause upwelling. This upwelling is different from the Somali upwelling because in this no strong current develops. In the southwest monsoon season a weak upwelling has been reported from the east coast of India (Varadachari and Sharma, 1967). Along the west coast of India, however, subsurface water comes very close to the surface, which has been taken as upwelled water (Banse, 1968).

The subtropical anticyclonic gyre includes the South Equatorial Current, the Agulhas Current and those portions of the westwind drift, which lie north of the subtropical convergence, close to 40°S.

The hydrographic structure of the Antarctic waters flowing into the Indian Ocean is very similar to those occurring in the Atlantic and the Pacific. It is governed by the surfacing of the main thermocline and by the strong deep-reaching Circumpolar Current forming the major bulk of the Indian Ocean deep and bottom water flowing northward.

(b) *Chemical*

The nutrient properties of the various water masses in the Indian Ocean are largely governed by the monsoon winds blowing over the northern Indian Ocean. A detailed review of all the data collected during IIOE has been published by McGill (1973). However, some general features of the chemical characteristics are as follows:

Because of a weak renewal and sluggish circulation, a thick layer of very low oxygen concentration extends from about 100 m to 1000 m almost all over the northern Indian Ocean. The oxygen content of this water is very often lower than 0.5 ml/l. Off the Indian coast values lower than even 0.05 ml/l have frequently been

reported. This feature of the Indian Ocean is very similar to that of the eastern tropical Pacific Ocean.

The monsoon gyre in the northern India Ocean is marked by high PO_4^{3-} -P contents, sometimes associated with low oxygen concentration due the effect of upwelling. Phosphate concentration in the region of Somali upwelling reaches values greater than $1 \mu\text{ mol/l}$ at the surface. For the south-western Indian Ocean the range is from 0.25 to $0.54 \mu\text{ mol/l}$. PO_4^{3-} -P concentrations, in general, increase with depth reaching a maximum between the depth range 300 and 500 m which remains almost similar throughout the water column. It, however, shows a slight decrease close to the bottom.

Values for NO_3^- -N indicate similar features, with higher values at the surface during the upwelling period. Generally, the NO_3^- -N concentrations range from $1 \mu\text{ mol/l}$ at the surface to about $40 \mu\text{ mol/l}$ between 3000 and 4000 m depth range. But during the periods of high photosynthetic productivity, the surface values quite frequently reach zero.

Marked changes in the concentrations of nutrients occur at 10°S . The monsoon gyre in the northern Indian Ocean is marked by high PO_4^{3-} -P concentration and within this region the concentrations range less than $0.4 \mu\text{ mol/l}$ to more than $1 \mu\text{ mol/l}$. In the areas of the sub-tropical gyre the nutrient values are very low.

Ryther and Menzel (1965) concluded the general levels of all the nutrients in the western Arabian Sea are about twice as high as those of the corresponding depths of the North Atlantic.

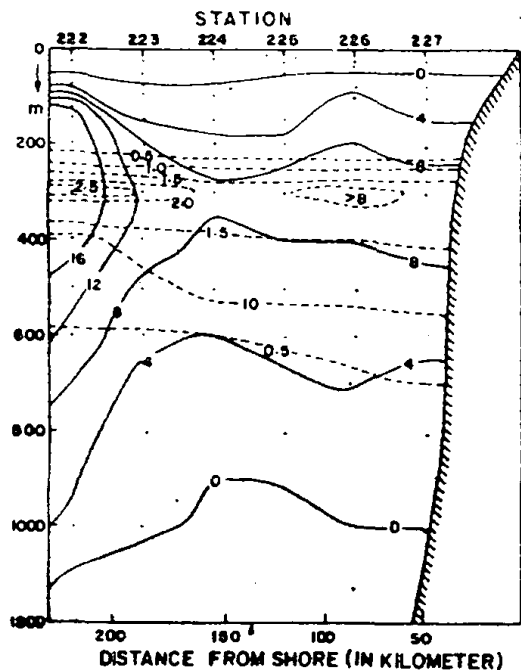


Fig. 3

Fig. 3.

Subsequent to IIOE much work has been done to study the quantitative aspects of the nutrient chemistry in the northern Indian Ocean (Sen Gupta *et al.*, 1975, 1976 a and b, 1977, 1979, 1980b; Naqvi *et al.*, 1978, 1982; Deuser *et al.*, 1978). These studies revealed that about one-third of the dissolved nitrate-nitrogen is lost during the process of denitrification in the oxygen-poor water layer of the northern Arabian Sea and this process could be traced to 2°N. Occasionally, two maxima of nitrite-nitrogen and two minima of oxygen are observed in this region. The depths of the maximum intensity of denitrification invariably coincide with the depths of the secondary nitrite maxima (Figure 3). The rate of denitrification is 200 g/m² in the waters of the northernmost part of the Arabian Sea, where the process of renewal of deeper water is very slow due to the sluggish movement of water (Qasim, 1982). This rate gets reduced to 70 g/m² at 15°N (Sen Gupta *et al.*, 1980b), and farther south, at 12°N it is 45 g/m² (Naqvi *et al.*, 1982). This is equivalent to 5-10% of the global rate of denitrification required to maintain a steady state in the distribution of nitrogen on the surface of the earth (Emery *et al.*, 1955).

Assuming that only about 10% of the photosynthetic productivity reaches below the euphotic zone (Deuser, 1971) and about 1% of the total production results in denitrified nitrogen (Deuser *et al.*, 1978), it has been calculated that the mean 'residence time' of water masses between 75 and 1200 m in the northern Arabian Sea can be expected to lie in the range 43-54 years (Sen Gupta *et al.*, 1980b). A 'residence time' of 30 years has been suggested by Hartmann *et al.* (1971) based on the data on the rate of outflow from the Gulf. This outflow has been found to be of the order of 3×10^3 km³/year.

Based on the oxidative ratios of the nutrients, the ratios of change of carbon : silicon : nitrogen : phosphorus in the waters of the northern Indian Ocean have been calculated as 108 : 40 : 16 : 1 by atoms. These agree fairly well with the atomic ratio of concentration of nitrogen : phosphorus in plankton of the Indian Ocean which is 15.4 : 1.

Silicate concentrations in the deeper waters of the Indian Ocean are higher than those at the corresponding depths of the other two oceans. It has been observed that silicate values can be used to identify different water masses by plotting them against the sigma-t values. This has also been confirmed by examining the relationship between silicate and oxygen consumption. The relationship shows that beyond a certain concentration of silicate, the relation becomes asymptotic indicating that the water masses having such silicate and oxygen concentrations originate from a similar source (Sen Gupta *et al.*, 1976b).

(c) *Biological*

Several atlases on the phytoplankton and zooplankton production in the Indian Ocean have been published based on the data collected during the IIOE (Krey and Babenerd, 1976; IOBC, 1968a and b). More recently both primary and secondary

production rates of the Indian Ocean in relation to various relevant factors have been estimated by Qasim (1977). The gist of the information is presented below.

The euphotic zone or the compensation depth (1% of the surface illumination) in the Indian Ocean varies between 40 and 120 m, increasing with depth from coastal to offshore regions.

The range in column production varies from 0.001 to 6.5 gC/m²/day. Areas of high productivity lie mostly in the coastal and upwelling zones. These include the Gulf and of Oman, mouth of the Indus river, Saudi Arabian waters, Somalia and Mozambique coasts, south-west coast of India, mouth of the river Ganga, Burma

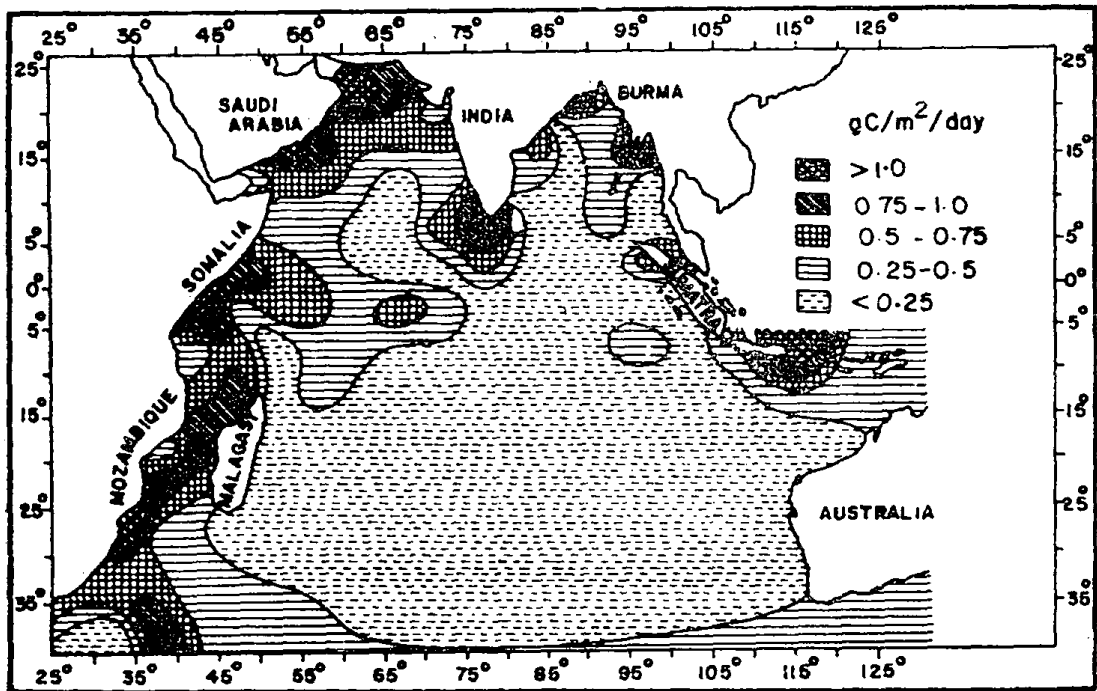


Fig. 4.

coast, and off northern Sumatra Java (Figure 4) The average production in the coastal areas works out to be 485 gC/m²/years as compared to the offshore average of 229 gC/m²/year. Total photosynthetic productivity in the Indian Ocean has been found to range from 3 to 6 × 10⁹ tonnes C/year with an average of 4.5 × 10⁹ tonnes C/year or 258 mgC/m²/day.

An analysis of the data indicates that the Arabian Sea and the Bay of Bengal are the two most productive regions of the Indian Ocean. The total column production in the Arabian Sea works out to 1.1 × 10⁹ tonnes C/year, while the same for the Bay of Bengal is 0.4 × 10⁹ tonnes C/year. This means that these two areas account for about one-third of the total photosynthetic productivity of the Indian Ocean though they together occupy only about 14% of the total area. There is, however, a qualitative difference in the productivity of these two areas. The surface

THE INDIAN OCEAN—AN ENVIRONMENTAL OVERVIEW

productivity (1m depth) is 4.9 tonnes C/km²/year for the Bay of Bengal while the same for the Arabian Sea is 3.9 tonnes C/km²/year. This anomalous situation in the column and surface productivity in these areas has been attributed to greater cloud cover and higher surface nutrient load, particularly, nitrate-nitrogen, in the Bay of Bengal than in the Arabian Sea (Qasim, 1977).

The zooplankton biomass in the Indian Ocean varies from 15 to 50 ml/m². The areas of high abundance mostly coincide with those of high photosynthetic productivity. The total zooplankton biomass has been estimated to be 5.2×10^8 tonnes/year (Prasad *et al.*, 1970). Secondary production computed from the zooplankton biomass works out to 69.3×10^6 tonnes C/year the whole Indian Ocean.

Studies on the benthic production of the Indian Ocean revealed an expected decrease from shallower to deeper water. But the density of meiofauna was greater than that of the macrofauna in deeper waters. Benthic population was larger in the areas of high productivity. However, the upward movement of water, bottom configuration and the types of sediments control the abundance of macrofauna. Average benthic biomass in the Arabian Sea upto a depth of 2100 m was 1.8 gC/m²/year, while the same in the Bay of Bengal, upto a depth of 1870 m, and in the Andaman Sea (upto a depth of 1820 m) were 0.5 and 1.2 gC/m²/year respectively (Harakantra *et al.*, 1980; Ansari *et al.*, 1977; Parulekar and Ansari, 1981). Extrapolating these values to the whole of the Indian Ocean, the annual benthic production works out to be 89.9×10^6 tonnes in terms of carbon.

Recent figures of pelagic, demersal and crustacean resources from the different regions indicate that the annual catch for the Indian Ocean is about 4 million tonnes (FAO, 1978). Thus, the Indian Ocean, occupying an area of 20.8% of the world oceans, yields only 8.2% of the global fish catch. The potential yield of the Indian Ocean has been estimated as 14.2×10^6 tonnes/year (Qasim, 1977). Therefore, there is much scope for increasing the fish production of the Indian Ocean by increasing the effort.

(d) Geological

The contour maps of the Indian Ocean, relative to the equator, indicate the asymmetric shape imposed by the existence of the Asian continent (Dietrich and Ulrich, 1968). Due to such an asymmetry the Indian Ocean gets separated from the deep reaching vertical convection areas of the Northern Hemisphere. Recent geophysical investigations indicate that the Indian Ocean is the most complex of the three major oceans as regards its history of formation and hence its physiography, probably because of this asymmetric formation (Mckenzie and Sclator, 1971). Measurements of its magnetic field showed that the floor of this ocean is spreading at the rate of 2 cm/year and implies that the Indian Ocean is about 10⁸ years old (Dietrich, 1973).

One of the most prominent topographic features of the Indian Ocean is its seismically active, rugged inverted Y-shaped Mid-Indian ridge, which is cut by

numerous north-northeast trending fracture zones (Figure 5, given by Heezen and Tharp, 1964). Microcontinents and meridional aseismic ridges, e.g. the ninety-east ridge 4800 km long and the Chagos-Laccadive Plateau, are the unique features of the Indian Ocean (Heezen and Tharp, 1964).⁹ These features, although massive, are relatively smooth-surfaced blocks and in marked contrast to the rugged features of the Mid-Indian ridge. Like in the other oceans, there are a good number of deep basins in between the topographic highs of the Indian Oceans.

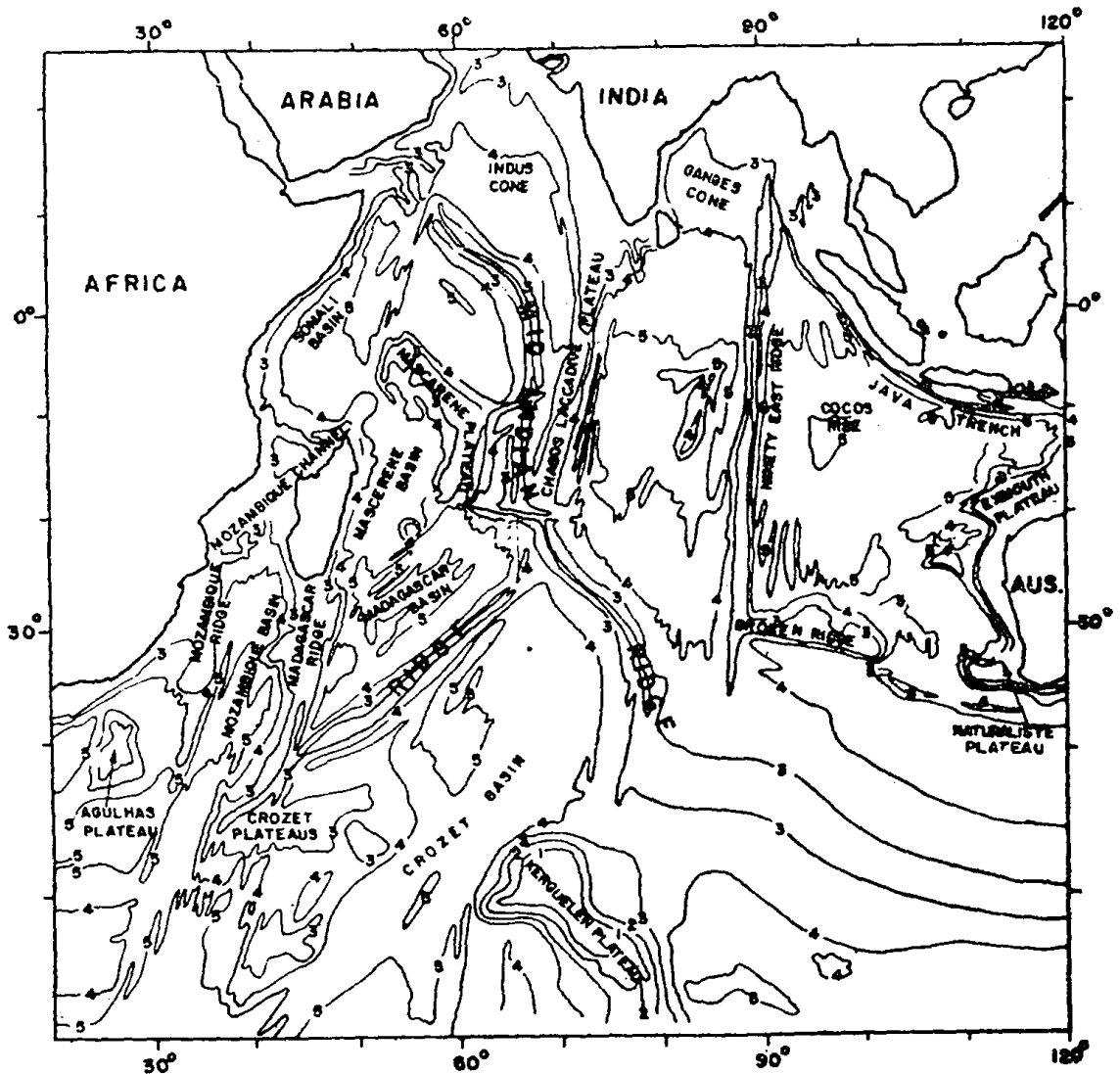


Fig. 5.

Sediment cones and abyssal plains with sediment thickness exceeding 1.5 to 2.5 km. are present in the Bay of Bengal, Arabian Sea, Somali basin and Mozambique basin (Ewing *et al.*, 1969). In parts of the Ganges cone, sediment thickness exceeds

12 km (Curry & Moore, 1971). In the high southern latitudes near the polar front, smooth, 'swale' topography with moderate sediment thickness appears as a result of higher productivity of the Antarctic Ocean, while in the other areas, and especially in the topographic highs, the sediment is very thin (Venkatarathnam and Hayes, 1974).

The complex physiography, the asymmetrical distribution of the surrounding continents, their varying geology and climate, and the northward closure of the Indian Ocean preventing the influence of colder northern latitudes have a considerable effect on the fauna and the sediment characteristic in the northern part of the Indian Ocean. Moreover, the Indian Ocean receives about 34×10^8 tonnes of suspended sediment per year from the rivers draining into it (Holeman, 1968). Almost half of this or about 16×10^8 tonnes are added by the river systems of the Indian sub-continent.

In terms of areal extent, the most extensive sedimentary facies in the Indian Ocean is the calcareous sediments. It occupies the Mid-Indian ridge. The other more shallower areas are neither influenced by terrigenous influx nor by the influx of siliceous skeletal remains (Venkatarathnam and Hayes, 1974). The critical depth at which calcium carbonate becomes a minor component varies with latitude (Lisitzin, 1971).² The other sedimentary facies are : terrigenous clay adjacent to the major river basins; siliceous clay and ooze in the equatorial and southern latitudes influenced by high biological productivity; brown and red clays in deep areas outside the productivity belts and the areas of terrigenous influx (Venkatarathnam and Hayes, 1974; Siddiquie *et al.*, 1976a & b). Although the areal extent of terrigenous sediment is relatively small, because of its enormous thickness, its volume exceeds 70% of the total sediments of the Indian Ocean (Ewing *et al.*, 1969). Within the limits of the broad features noted above, Venkatarathnam and Hayes (1974) mapped the following materials in the Indian Ocean : (i) hard rocks (volcanic and limestones) on topographically high areas, especially on the Mid-Indian ridge; (ii) Mn-nodules in the deep basins and Agulhas Plateau far removed from terrigenous sediment supply; and (iii) silicic volcanic ash in the eastern Indian Ocean adjacent to the Indonesian archipelago. In addition, deposits of ilmenite placers have been mapped in the coastal regions of several of the countries bordering the Indian Ocean, e.g. India, Australia and Sri Lanka.

Nature of Environmental Problems

Almost all the countries bordering the Indian Ocean are developing countries. Their major source of revenue is agriculture industry and in some countries also mining. The effects of pollution in the marine environment, largely arising out of the economic activities, began to be felt only recently although the practices have continued over a long period of time. These problems, however, are largely confined to the coastal areas of most countries, although because of the prevailing wind

system, the patterns of water circulation and the nature of bottom topography, the effects can have far-reaching implications.

While a few of the problems are quite chronic in some countries, they are relatively simple in others. In this communication no attempt has been made to differentiate them and hence it is greatly hoped that most of the problems presented here would be of general interest.

(a) *Domestic Sewage and Industrial Effluents*

Due to increasing urbanization and industrialization throughout the region, the volume of sewage and industrial waste production is constantly on the increase. Many countries have several large rivers flowing through the landmass, but because of increased human activities around them many of these rivers have become badly polluted. These two human activities also contribute quite substantially to the degradation of the adjoining seas. Sewage and industrial wastes in these countries, either untreated or partially treated, are allowed to be discharged into the rivers and seas. The magnitude of treatment undertaken can, perhaps, be assessed from the fact that in a country like India, only 42 cities, with a population of over 100,000 have arrangements for sewage treatment. Hardly 50% of the total population in the countries bordering the Indian Ocean is provided with proper sanitation arrangements. The result is that high counts of coliform bacteria are often found on the beaches and in coastal waters.

Examination of the concentration of toxic metals, such as, Hg, Cd and Pb reveals that in plankton and in fishes the levels of these metals are still much lower than the acceptable maximum for them in many industrialized countries.

(b) *Agricultural Wastes*

Fertilisers, pesticides and insecticides are quite abundantly used in the developing countries in agriculture, pest control and vector control. The quantities of pesticides and insecticides used every year vary from 45000 tonnes in India to 3.5 tonnes in Bangladesh (NIO, 1976). In many countries, however, organochlorine pesticides are either prohibited or are gradually being replaced by organophosphorus and carbamate pesticides. Very little study on their accumulation and harmful effects has been carried out. However, a recent survey has shown that plankton in the Arabian Sea, off the west coast of India, has DDT concentration ranging from 0.05—3.21 ppm wet weight (Kureishy *et al.*, 1978).

Use of these harmful organochlorine and organomercurial pesticides have been totally banned in all the industrial countries of the world. But their total production has not been reduced, rather, a relative increase in their manufacture is taking place. A hypothesis has very recently been suggested that there should be a 'southward' tilt of the concentration of organochlorine and organomercurial pesticides in the marine environment.

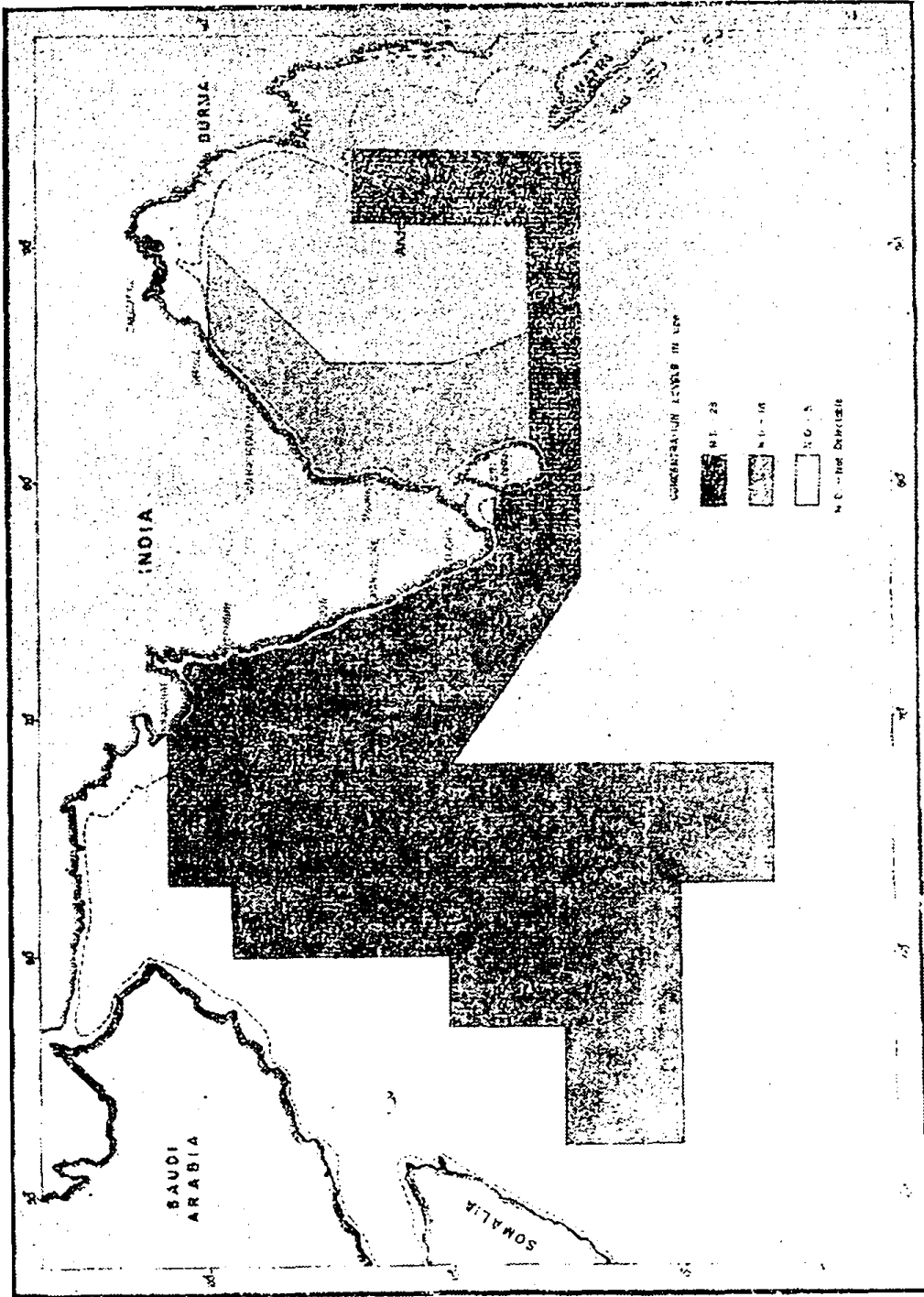


Fig. 6. Dissolved Petroleum Residues in Indian Ocean.

(c) *Radioactive and Thermal Wastes*

In countries of the Indian Ocean region, power generation is mostly thermal. But in some countries, nuclear power is also being generated. So far no serious harm has been reported from these sources, although fly ash from thermal power plants invariably creates environmental problems.

Radioactive wastes from nuclear power plants are normally disposed off according to strict international conventions. However, their heat generation poses several problems. Nuclear power plants normally release 50% of the generated heat to the coastal marine environment. Flora and fauna in the warm tropical waters live dangerously close to their upper lethal limits of temperature, particularly during the warm summer months. They do not need a large deviation from this limit to finally end up with catastrophic effect. Release of hot salty water, when coupled with wind system, alters the current and mixing patterns from offshore to onshore. This is more probable in tropical areas where the range of the semi-diurnal tides is quite high.

(d) *Tourism*

In developing countries more and more emphasis is being given towards the promotion of tourism. The result is that too many large hotels are being constructed along the beaches. Wastes from these hotels very often pose serious problems in the adjacent marine area. In some countries garbage and other wastes from the hotels have spoilt the beauty of the beaches leading to contamination of the environment and generation of hydrogen sulphide in the water.

(e) *Oil Spills*

In 1982 the global marine transport of oil was 1270 million tonnes (MT), of which 579 MT or 43% of the total was shipped from the Gulf countries (BP, 1982).

The main routes of marine transport of oil from the Gulf countries are across the Arabian Sea. One of these is through the Mozambique Channel round South Africa to the Western Hemisphere, while the other one is round Sri Lanka across the southern Bay of Bengal through the Malacca Strait to Far East and Japan (Figure 6). In 1982, 331 MT of oil was shipped to the Western Hemisphere and 248 MT to the Far East and Japan from the Gulf countries. This, coupled with the increasing emphasis on offshore oil exploration in many countries of the region, make the northern Indian Ocean very vulnerable to oil pollution.

Sources of oil pollution are tanker disasters, ballast water and bilge washings. Fortunately, only a few tanker disasters have occurred, so far, along these tanker routes. However, the effect of the oil pollution can be seen on the beaches in the form of deposits of tar-like residue. The frequency and intensity of this residue depend on the current direction along the coastal regions. Because of the monsoon

winds, the surface currents change the direction every six months. Whenever a shoreward component of current develops, heavy deposition of tar balls occurs on the beaches.

It has been calculated that at any time the amount of floating tar in the surface layers of the Arabian Sea would be about 3700 tonnes, while along the tanker route across the southern Bay of Bengal the tar would amount to 1100 tonnes (Sen Gupta and Kureishy, 1981). This agrees well with the intensity of tanker traffic and the volume of oil transported through the two areas.

(f) *Coral Reefs and Mangroves*

Coral reefs and mangroves occur widely in almost all the Indian Ocean countries. Damages that can occur to these two ecosystems as a result of over-exploitation of the reefs or mangroves or because of pollution are quite extensive. These can be summarized as follows :

- (i) *Coral Reefs* : Coral reefs of the tropical Indian Ocean include fringing and barrier reefs ; sea-level atolls ; and elevated reefs (Stoddart, 1972). The areas of their occurrences are : NW and SE coasts of India, Laccadive Islands, Andaman and Nicobar Islands, Maldiv Islands, Chagos Archipelago; Seychelles, Mauritius, Aldabra and Comores Islands, coasts of Kenya, Tanzania and West Malagasy. Radiocarbon dating of some of the coral reefs has indicated their ages as more than 2000 years (Stoddart, 1972). The growth rate of corals in the Atlantic has been found to be 0.15—0.5 cm/year by ^{228}Ra (Moore and Krishnaswami, 1972). The growth rate of the corals in the Indian Ocean can be assumed to be of a similar order/

Most of the coral reefs in this region have been declared as endangered ecosystems. Several coral reefs have almost disappeared because of the withdrawal of coral debris and live corals as a raw material for cement industry, while others have become dead due to their constant exposure to pollutants, particularly oil. Examples of this are : the region of Kavaratti reef in the Laccadives ; reefs found in the southern part of the Great Nicobar Island in the Andaman group ; and SW part of Malagasy. Dredging for the construction of jetties and works connected with the development of harbours have destroyed some of the coral reefs of the Mahe Island in the Seychelles.

- (ii) *Mangroves* : Mangroves constitute an important resource in the region and form spawning grounds, nurseries and feeding grounds for economically important fishes and crustaceans. They act as a buffer zone and offer protection to vulnerable communities like the coral reefs. They also stabilise the bottom sediments, control the local mean water level and the direction of flow. Mangroves constitute a significant portion of the coastal wetland in many countries and a fairly large percentage of human popu-

lation is dependent on them. For example, about one-eighth of the Bangladesh wetland is mangrove and one-third of the total population of that country is either directly or indirectly dependent on the mangrove ecosystem (UNESCO, 1979).

Due to ever increasing demand for land and fuel, many mangrove areas of the Indian Ocean region have been destroyed. This has led to heavy siltation in the nearshore region and with no protective cover of mangrove, the devastation of men and material during the cyclones in coastal areas is immense. Mangroves occur in profusion along NE coast of India, Bangladesh, Malaysia, Sri Lanka, Mauritius, Seychelles and Indonesia.

(g) *Siltation*

As noted above, the Indian Ocean receives annually 34×10^8 tonnes of suspended sediment (Holeman, 1968), half of which or about 16×10^8 tonnes comes from the rivers flowing through the Indian sub-continent. This quantity is on the increase due to human activities, such as, mining on land, clearance of land for agriculture, lumbering, urbanization and industrialization, and dredging to deepen harbour channels and estuaries.

Most of the silt settles near the river mouths and in coastal areas. This probably decreases the productivity of water and depletes fishery resources. Although these effects have been indicated in many countries, not much direct evidence has been obtained on the influence of siltation on marine and estuarine fisheries.

These then are the potential marine pollution problems, chronic or acute, direct or indirect, in the countries in the Indian Ocean region.

Research and Monitoring Activities

Monitoring and research on marine pollution are fast developing activities in many countries of the Indian Ocean region. Surveys for the collection of baseline data on almost all of the potential pollutants in the marine environment are under progress and a fairly good data base has been built up. These data are mostly on the environmental conditions in the coastal and nearshore regions and also on some parts of the open areas of the Arabian Sea and the Bay of Bengal including the adjacent areas of the Laccadive and the Andaman group of islands. Several reviews of all these investigations have been published in recent years (Qasim and Sen Gupta, 1980, 1983 a and b). The following details have been extracted from these publications combining with data collected subsequently.

(a) *Petroleum Hydrocarbons*

In all, 6689 observations were made on oil slicks and other floating pollutants along the tanker and trade routes across the northern Indian Ocean. Of these oil was

sighted on 5582 occasions or 83.5% of the total number of observations (Sen Gupta and Kureishy, 1981). The data were then plotted in 5°-squares. The percentage of oil sightings ranged from 51 to 96. The number of oil sightings increased away from the source of oil, i.e. from the Gulf region. Even in areas away from the tanker and trade routes, the percentage of oil sightings was almost of a similar order. The occurrence of tanker disasters has not been very significant along these routes fortunately so far. Therefore, it could be concluded that oil is released in this region mainly from the ballast and bilge washings of the ships and that the northern Indian Ocean is a well known area for the occurrence of oil slicks.

Observations on the floating petroleum residues from the Indian Ocean region, are presented in Table 1 as ranges in values (Sen Gupta *et al.*, 1980a ; Fondekar *et al.*, 1980 ; Sen Gupta and Kureishy, 1981 ; Topgi *et al.*, 1980). As expected the concentrations show variations in time and are fairly high occasionally along the tanker routes. In the Arabian Sea the concentrations range from 0 to 6.0 mg/m² with a mean of 0.59 mg/m². The range in the Bay of Bengal tanker route varied from 0 to 69.75 mg/m² with a mean of 1.52 mg/m². This, probably, indicates that the tanker route in the Bay of Bengal is relatively more polluted than that of the Arabian Sea.

Observations in March 1981 along the east-going oil tanker route across the Arabian Sea, between 12° and 19°N and 70° and 74°30' E, indicated a range of 0.3—112.2 mg/m² with an average of 12.7 mg/m² for the floating tar balls. This may, perhaps, indicate that oil pollution in the Arabian sea is on the increase.

A number of observations were taken along the west-going tanker route on the Arabian Sea during June-September 1983 (Table 1). Absence of floating tar balls in this region during this period was expected, as the surface currents on the Arabian Sea normally flows directed towards the Indian west coast during the SW monsoon months.

Applying the average concentrations of floating tar balls to the areas of the Arabian Sea (6.225×10^6 km² from 0°—25°N and 50°—80°E) and the tanker route across the southern Bay of Bengal (0.73×10^6 km² from 5°—7°N and 80°—95°E) the total quantity present comes to 3700 and 1100 tonnes for these two areas respectively.

Accumulation of floating tar is entirely dependent on the surface currents. In the areas of strong surface currents, e.g. the Gulf Stream and Kuroshio, heavy accumulation of tar particles have been observed. The observed concentration in the North Atlantic ranged from 0.12—0.64 mg/m² with a maximum of 91.8 mg/m² (Levy and Walton, 1976). Similar accumulation in the Northwestern Pacific ranged from 0.02—13.3 mg/m² (Sano *et al.*, 1979). Thus, the oil tanker routes in northern Indian Ocean appear to be as much polluted as those in the other oceans.

If we assumed that the abundance of oil entering any marine area is proportional to the volume transported, the average amount of oil present in the seas around India is 0.36% of the total flow, 1% of the total input ends up as floating tar and the volume transported across the Bay of Bengal tanker route is 35% of the total transport across the Arabian Sea, then the 'residence time' of floating tar in

TABLE 1
Dissolved/Dispersed hydrocarbons and particulate petroleum residues (tar balls) in the Arabian Sea and Bay of Bengal

		Arabian Sea		Bay of Bengal	
		Dissolved/Dispersed hydrocarbons ($\mu\text{g}/\text{kg}$)			
Coastal area	Surface	8.6—31.0	(March 1978)	Surface	0—2.3 (June 1978)
	"	10.6—17.7	(Oct. 1983)	"	0—4.5 (Aug. 1981)
Tanker route	Surface	17.1 \pm 4.1	(March 1978)	Surface	21.7 \pm 1.0 (June 1978)
	"	21.5—42.8	(Dec. 1978)	"	75.2 \pm 10.0 (Feb. 1979)
	"	18.6—41.6	(Dec. 1978)	"	5.3—27.4 (Jan. 1980)
	"	6.4—9.0	(Feb. 1980)	"	6.4—11.2 (Feb. 1980)
	"	47—230	(Oct. 1980)	10 m	23.2—26.9 (June 1978)
	"	200—305	(March 1981)	"	22—94 (Feb. 1979)
	"	3.0—8.9	(July 1983)	"	2.2—20.0 (Jan. 1980)
	"	7.4—16.2	(Sept. 1983)	"	3.1—13.6 (Feb. 1980)
	"	5.7—10.6	(Oct. 1983)	20 m	13.1—28.2 (June 1978)
	"	5.1—12.4	(Nov. 1983)	"	24—73 (Feb. 1979)
	10 m	0.9—22.9	(March 1978)	"	1.6—27.1 (Jan. 1980)
	"	16.8—42.5	(Dec. 1978)	"	1.2—9.0 (Feb. 1980)
	"	16.9—34.5	(Dec. 1979)		
"	3.1—6.3	(Feb. 1980)			
"	77—210	(Oct. 1980)			
"	130—267	(March 1981)			
"	0—1.2	(July 1983)			
"	3.4—8.5	(Sept. 1983)			
"	2.1—5.4	(Oct. 1983)			
"	1.4—6.1	(Nov. 1983)			
				Range	Bay of Bengal
				Arabian Sea	0—28.2
				Average Value	4.6
					15.8

20 m	25—28	(June 1978)
"	28.6—37.5	(Dec. 1978)
"	10.4—24.9	(Dec. 1979)
"	2.4—4.5	(Feb. 1980)
"	0—1.0	(July 1983)
"	0—1.2	(Sept. 1983)
"	0—1.1	(Oct. 1983)
"	0—1.6	(Nov. 1983)

Particulate Petroleum Residues (tar balls) (mg/m³)

Arabian Sea

Tanker route	0.02—	0.32	(March 1978)
	1.26—	3.46	(June 1978)
	0—	0.54	(Dec. 1978)
	0.09—	6.0	(May 1979)
	0—	0.53	(Feb. 1980)
	0.30—	112.2	(March 1981)
	0—	0.06	(Feb. 1982)
	0—	PI	(June 1983)
	0—	—	(July 1983)
	0—	PI	(Sept. 1983)

Bay of Bengal

	0.42—	3.45	(June, 1978)
	0—	1.6	(Jan. 1980)
	0—	69.8	(Feb. 1980)
	0—	PI	(Jan. 1984)

the northern Indian Ocean ranges from 33 to 38 days (Sen Gupta and Qasim, 1982). The average tar concentration on the surface of the North Atlantic has been calculated as 5200 tonnes and its 'residence time' is about 58 days (Levy and Walton, 1976). Thus, it can be concluded [that tar found in the sea remains unchanged from 30 to 60 days.

As can be seen from Table 1, the concentrations of dissolved and dispersed petroleum hydrocarbons from the surface to 20 m were almost uniform, excepting some occasional high values. However, some seasonal variations, seen from the Table, may be due to differences in the intensity of tanker traffic from month to month and because of the changes in the meteorological conditions.

The average concentrations of dissolved petroleum hydrocarbons in the upper 20 metres of the tanker routes in the Arabian Sea and the Bay of Bengal were 42.8 and 28.2 $\mu\text{g}/\text{kg}$ respectively. Calculating the volumes in the upper 20 m from the total areas, mentioned earlier, the quantity of petroleum hydrocarbons present in the uppermost 20 m of the water column would be about 5×10^6 tonnes in the entire Arabian Sea and 0.4×10^6 tonnes in the Bay of Bengal tanker route. Summing up of all the values in Table 1 would result in Figure 6, depicting the dissolved petroleum residues in the northern Indian Ocean, as of 1983.

A few observations on the concentration of petroleum hydrocarbons in zooplankton and in the sediments of the Arabian Sea off the west coast of India are also available (Fondekar *et al.*, 1980). In zooplankton the concentration was found to range from 19.5—83.3 $\mu\text{g}/\text{g}$, while in the sediments the range was 4.8—8.5 $\mu\text{g}/\text{g}$, both on dry weight basis.

Deposition of tar-like residues on the beaches is more or less a chronic problem in almost all the countries bordering the Indian Ocean. However, this is a seasonal phenomenon depending on the pattern of coastal circulation largely regulated by the monsoons. Records from the west coast of India during the years 1975 and 1976 indicate a range of 22 to 448 g/m^2 with a peak value, on one occasion, of 1386 g/m^2 (Dhargalkar *et al.*, 1977). Observations on the beaches in Kenya gave a range of values of 20 to 2400 $\text{g}/100 \text{m}^2$ (EAMFRO, 1973). Tar lumps as heavy as 16 kg have, sometimes, been observed on Kenyan beaches.

(b) *Heavy Metals other than Mercury*

- (i) *In Water* : Some data on the concentrations of heavy metals, in dissolved form, are available from the Indian Ocean region. These are given in Table 2, without indicating the horizontal and vertical variations as these samples were collected from different areas and at different depths of the Indian Ocean including some areas off the Indian coast. The large ranges seen in the Table may be due to different analytical techniques used. The ranges are : Cu 0.08—49.1 ; Cd 0.01—1.88 ; Fe 0.10—96 ; Mn 0.07—80 ; Zn 0.3—42.4 ; Pb 0.02—7.5 ; Ni 0—16.3 ; and Co 0—7.9 all in $\mu\text{g}/\text{l}$. The accuracy and reproducibility of the data on trace metals have always been subjected

TABLE 2
 Ranges of Dissolved Heavy Metal Concentrations ($\mu\text{g/l}$) in the Indian Ocean

Source	Cu	Cd	Fe	Mn	Zn	Pb	Ni	Co	Hg(ng/l)
Topping (1969) Chester & Stoner	0.5—49.1	—	0.1—61.8	0.1—4.6	3.9—19.5	—	—	—	—
(1974) Surface only	0.2—1.2	0.02—0.14	0.5—3.1	0.07—0.37	0.3—3.0	—	0.3—2.6	—	—
Sen Gupta et al. (1978 b)	1.7—7.9	—	7.2—66.9	—	0.5—42.4	—	0—11.5	0—6.6	—
Singbal et al. (1978)	—	—	—	—	—	—	—	—	13—187
Sanzgiri & Moroes (1979)	1.9—19.9	—	8.5—96	1.8—80	1.2—29.7	—	0—16.3	0—6.7	—
Danielsson (1980)	0.08—0.48	0.01—0.16	0.15—10	—	0.6—13.8	0.02—0.18	0.18—0.95	0—0.02	—
Sanzgiri et al. (1979)	—	—	—	—	—	—	—	—	0—204
Braganca & Sanzgiri (1980)	22—37.2	—	6.2—131.5	1.8—40.8	2.4—20	—	0—12.2	0—7.9	—
Sanzgiri & Braganca (1981)	1—5	0.15—1.9	2—21.7	1.5—24.7	1.2—12.8	0.25—7.5	0—1	0—1	—

TABLE 3
 Ranges of Concentration of a Few Essential & Non-essential Heavy Metals (PPM wet weight) in Zooplankton, Crustaceans, Bivalve & Muscles of certain Fishes from the Northern Indian Ocean

Fish	Essential Heavy Metals					Non Essential Heavy Metals			
	Cu	Fe	Mn	Zn	Ni	Co	Pb	Cd	Hg
Zooplankton	2.0—5.0	35.0—94.0	3.0—7.0	8.0—31.0	0.2—3.0	ND—4.0	1.0—12.6	0.02—5.99	ND
Prawns (6 Spp)	3.5—24.0	—	—	—	—	—	<1.0	0.2—2.5	ND—0.17
Crabs	0.7—13.5	—	—	—	—	—	<1.0—7.88	0.61—1.12	0.004—0.01
Clams	—	—	—	—	—	—	1.28	1.66	0.06
Oysters	45.0	—	—	—	—	—	<1.0	1.36	0.02
Mussels	—	—	—	—	—	—	1.31	1.38	0.09
Flying Fish	0.1—0.7	4.0—62.0	ND—3.7	4.0—21.0	ND—0.9	0.2—1.3	1.08—5.76	ND—0.65	ND—0.07
Silver Bellies	1.0—1.6	—	—	—	—	—	<1—3.21	0.58—2.11	0.001—0.01
Malabar Anchovies	4.4	—	—	—	—	—	<1	0.7	0.01
Sardines (2 Spp)	0.03	8.0—10.0	0.2	4.5—6.3	—	0.7—1.1	<1	ND—0.62	ND—0.01
Mackarel (2 Spp)	1.0—1.3	12.0	0.01	6.0	ND	1.8	<1	0.22—1.62	0.01—0.02
Jew Fish (2 Spp)	ND—0.8	6.0—8.0	0.3—10.0	4.0—4.8	ND	0.7—1.1	<1—1.14	0.19—0.42	0.006—0.01
Perch (3 Spp)	0.2—0.7	6.0—29.0	ND—0.1	3.4—6.1	0.3—0.5	ND	<1	ND—1.47	0.007—0.1
Pilot Fish	0.1—4.9	—	—	—	—	—	<1—2.95	ND—0.83	ND—0.02
Scianid (2 Spp)	0.1—0.3	—	—	—	—	—	<1	0.86—1.36	ND—0.02

Sole	—	—	—	—	—	—	—	—	<1	0.35	0.01
Pomfret	—	—	—	—	—	—	—	—	<1	0.73	0.01
Cat Fish	—	—	—	—	—	—	—	—	1.02	0.92	0.06
Trevally (2 Spp)	ND—0.7	5.0—11.0	0.1—9.0	2.0—5.0	ND—0.6	ND—1.2	—	—	<1	ND—0.62	0.018—0.08
Grunter	0.36	—	—	—	—	—	—	—	2.7	ND	0.24
Talang	0.4	—	—	—	—	—	—	—	<1	ND	0.36
Tuna (4 Spp)	0.3—3.0	7.0—164.0	0.1—7.5	4.0—12.0	ND—4.0	ND—3.2	—	—	<1—3.3	ND—2.00	0.004—0.22
Dolphin Fish	0.2—1.7	13.0—39.0	ND—3.1	5.0—9.0	0.1—1.2	ND—1.9	—	—	<1—2.95	ND—0.95	0.01—0.14
Seer Fish	0.4	—	—	—	—	—	—	—	<1—1.5	0.25—0.66	0.09—0.11
Barracuda	0.1—0.5	4.0—17.0	0.2—3.1	3.3—5.8	0.1—0.3	0.6—1.9	—	—	<1	ND—0.28	0.06—0.2
Sea Pike	—	—	—	—	—	—	—	—	1.46	ND	0.11
Sharks (4 Spp)	0.14—1.1	10.0—57.0	ND—2.0	4.5—12.0	ND—0.3	ND—3.8	—	—	<1—6.02	ND—0.81	0.02—0.21

ND—Not Detectable

SOURCES : Kureishy et al., 1979, 1980, 1983, Unpublished.

to statistical treatment and only acceptable values have been reported in all the publications. Excepting copper all the higher values are either from the coastal region of the Indian mainland or off the coasts of oceanic islands. The higher ranges of iron, manganese and nickel are from the seas around Laccadive islands ; high cadmium and lead are from the sea around Andaman islands ; high zinc occurred off Bombay and high cobalt off the river mouths in the Bay of Bengal. An exceptionally high value of cadmium, 80 $\mu\text{g/l}$, was recorded in the polluted coastal waters off the city of Bombay (Ganesan *et al.*, 1980).

- (ii) *In Plankton and Fishes* : Available values (Kureishy *et al.*, 1981) of some of the metals in zooplankton from the Arabian Sea and Bay of Bengal gave the following ranges in ppm fresh weight : Cd 0.7—6.0 ; Cu 2—5 ; Mn 3—7 ; Zn 8—31 ; Fe 35—94 ; Pb 1—13 ; Ni 0.2—3 ; and Co 0—4 (Table 3). In all these analysis, the recovery was calculated with reference to the standard fishmeal obtained from International Laboratory of Marine Radioactivity, Monaco, and the values are the mean of at least triplicate analysis for every sample. Concentrations of all these metals have been analysed in 26 species of fish and crustaceans from both inshore and offshore regions of the northern Indian Ocean and in different parts of their tissues, such as, muscle, liver, gills and heart (Kureishy *et al.*, 1979 & 1981). Ranges of concentration in the muscles of these fishes of commercial importance, including sharks, are presented in Table 3. It can be seen from the table that concentrations of almost all of the metals, particularly the toxic metals such as Cd, Pb and Hg, are within the permissible limits for human consumption. It has been observed, in the same study, that the concentrations of all these metals in the livers of the dolphin fish (*Corryphaena hippurus* Linnaeus), barracuda (*Sphyraena picuda* Bloch), sharks (*Eulamia ellioti* Day), skipjack tuna (*Katsuwonus pelamis* Linnaeus), and yellowfin tuna (*Neothunnus macropterus* Schlegel) were significantly higher than in their muscles. This indicates that most of the metals are assimilated by these fishes in a fat soluble form. Acceptable correlation was, however, observed in the different fish tissues with their sexes, sizes and stages of maturity.
- (iii) *Mercury* : Because of its extreme toxicity and very harmful nature to human beings, concentrations of mercury in the water and biota have been treated separately. The study of mercury in the marine environment is relatively of a recent origin in India and hence data on this metal are very sparse.

(a) *In Water*

Mercury concentrations in dissolved form are normally found at the nanogram levels. Their sources are mostly industrial effluents, but some contribution can also be expected from weathering, leaching and atmospheric flux from deposits of

TABLE 4

Range and average concentrations of a few non-essential heavy metals (ppm wet weight) in different parts of fishes from the Northern Indian Ocean

Body Parts	Mercury		Cadmium		Lead	
	Range	Average	Range	Average	Range	Average
Muscle	N.D.—0.36	0.07	N.D.— 3.24	0.59	<1— 3.43	1.11
Liver	N.D.—0.04	0.01	1.2—87.3	20.18	<1—17.62	3.8
Gill	N.D.—0.03	0.016	N.D.— 0.76	0.42	<1— 7.0	3.14
Heart	N.D.—0.08	0.026	N.D.— 1.91	0.54	<1— 3.4	1.36
Kidney	N.D.—0.04	0.015	0.38—36.69	9.02	<1—69.46	8.61
Gonads	N.D.—0.03	0.015	N.D.— 8.06	1.25	<1— 4.76	1.36

SOURCES : KUREISHY *et al.*, 1979, 1981, 1983 (Unpublished).

TABLE 5

Mercury Pollution in and around Bombay City

Components	Coast	Distance from shore				Thana Creek
		1 km	1.5 km	2 km	3 km	
Water ($\mu\text{g/l}$)	1.4—23.0	12—29	10—35	9—30	14	42
Crab muscles (ppm wet weight)	0.2-4.1	0.1—1.5	0.2—1.0	0.3—1.3	1.8	7.3
Sediment (ppm dry weight)	0.1-27.0	—	—	—	—	38

SOURCE : Ganesan *et al.*, (1980).

mercury in the crustal rocks of the hinterland. High concentrations of mercury in the nearshore waters of the SW coast of India are probably due to deposits of mercury in the adjoining land. In the absence of any industrial source, such high concentrations ranging from 204 to 407 $\mu\text{g/l}$ in the surface waters of this area cannot be due to any other reason (Singbal *et al.*, 1978).

Ranges of all the observed values are presented in Table 2. Without taking into account the variation with depth the range is from 0 to 222 $\mu\text{g/l}$. However, a decrease occurs in the concentration of mercury with depth, as is the case with most of the other metals (Singbal *et al.*, 1978 ; Sanzgiri and Braganca, 1981).

(b) *In Plankton and Fishes*

An estimation of the total mercury concentration in plankton and fishes was carried out without fractionating the mercury into methyl and inorganic forms. In the organic matter, however, it can be assumed that mercury is present mostly in the methyl form and very little in the inorganic form.

The absence of mercury in zooplankton (Table 3) indicates that the metal is assimilated by fishes probably through other pathways of the food chain. Table 3 indicates that the mercury concentrations in the muscles of sharks and skipjack tuna are the highest values. Concentrations of non-essential heavy metals, Hg, Cd and Pb, in different tissues of the fishes from the Northern Indian Ocean (Table 4) indicate that their highest occurrence is in the liver and kidney. However, the highest concentrations of mercury, found in muscles, are still much lower than the internationally permissible maximum of 0.5 ppm of mercury for human consumption. Analysis of mercury in the muscles of several commercially important fishes from the inshore regions and from a polluted creek in and around the city of Bombay gave values ranging from 0.04—0.57 ppm on fresh weight basis (Tejam and Halder, 1975 ; Rama and Somayajulu, 1972). However, the concentration of the same metal, when analysed in 1980, in the water, crab muscles and sediments showed an increase by several fold (Ganesan *et al.*, 1980). These values (Table 5) also indicate a decrease in the mercury concentration away from the shore.

TABLE 6

Population and Related Data and Some Estimates of Pollutants Entering the Sea
Around India (as of 1984)

Population	720 million
Coastal population (25% of total)	180 million
Area of the Country	$3.276 \times 10^6 \text{ km}^2$
Agricultural area	$1.65 \times 10^6 \text{ km}^2$
Exclusive economic zone	$2.015 \times 10^6 \text{ km}^2$
River runoff (annual mean)	$1645 \times 10^6 \text{ km}^3$
Rainfall per year (on land)	$3.5 \times 10^{12} \text{ m}^3$
Rainfall per year (on Bay of Bengal)	$6.5 \times 10^{12} \text{ m}^3$
Rainfall per year (on Arabian Sea)	$6.1 \times 10^{12} \text{ m}^3$
Domestic sewage added to the sea by coastal population per year (@ 60 l per head/day)	$3.9 \times 10^9 \text{ m}^3$
Industrial effluents added to the sea by coastal industries per year	$0.39 \times 10^9 \text{ m}^3$

Sewage and effluents added by the rivers to the sea per year	$50 \times 10^6 \text{ m}^3$
Solid waste and garbage generated by coastal population per year (@ 0.8 kg per head/day)	53×10^6 tonnes
Fertiliser used per year (@ 30.5 kg/ha. yr ⁻¹)	5×10^6 tonnes
Pesticides used per year (@ 336 g/ha. yr ⁻¹)	55 000 tonnes
Synthetic detergents used per year	125 000 tonnes
Oil transported across the Arabian Sea in 1982	579×10^6 tonnes
Oil transported to Western Hemisphere in 1982	331×10^6 tonnes
Oil transported to Far East and Japan in 1982	248×10^6 tonnes
Tar deposition on beaches along the West Coast of India per year	750—1000 tonnes

TABLE 7

Concentrations of a few Heavy Metals (in $\mu\text{g/l}$) in Ice and Water, Princess Astrid Coast, Antarctica and in a Glacier in the Kashmir Himalayas

Station	Fe	Zn	Cu	Mn	Ni	Co	Pb	Cd
Antarctic Ice	1.4	14.4	3.0	6.8	2.0	0	0	0
Antarctic Lake	50.5	13.6	3.4	5.6	3.2	0	0	0
Himalayan Glacier (mean)	82.5	4.5	4.1	17.0	1.8	1.1	3.1	0

- (iv) *Chlorinated Hydrocarbons* : Only a few analyses of DDT and its metabolites in zooplankton have been carried out so far. In most cases, the values were below the detection limit. There was a direct relationship between DDT concentration and lipid content in the plankton, which indicates that the pathway of chlorinated hydrocarbons to the animal tissues is via the fat. The presence of BHC and PCB was also detected in the samples. The total DDT concentrations in plankton of the northern part of the west coast of India appears to be somewhat higher.

The values of organochlorine and organophosphorus pesticides in some of the fishes from the Indian Ocean region, particularly the plankton feeders, may be appreciably high because of the wide use of pesticides in agricultural activities in the countries bordering the Indian Ocean.

- (v) *Input Studies* : Data on the input of different cations and anions to the Indian Ocean are very scanty. Background data on sources of input, e.g., river runoff, load of silt, volume of domestic sewage and industrial effluents, rainfall, and aerosol are not available from all parts of the region.

However, some data are available from India (Table 6). A rough approximation for all the countries can, perhaps, be obtained by extrapolating the data given in Table 6, in relation to population density.

Most of the cations and anions, added to the oceans, are adsorbed on to the silt particles. Considering the enormous amount of silt added annually to the Indian Ocean, i.e. 34×10^8 tonnes (Holeman, 1968), siltation may be assumed as one of the principal sources of input.

The mean concentrations of some elements in the rain water from the coastal region of India were: Na 4.6; Cl 6.8; Ca 1.34; Mg 0.51; K 1.02 all in mg/l; Mn 23.4; Br 33.6; I 13.3 all in $\mu\text{g/l}$ (Sadasivan, 1979); Fe 4.3; Co 0.1; Ni 0.1; Cu 6.8; Zn 13.3; Pb 21.5 all in $\mu\text{g/l}$ (Fondekar and Topgi, 1979). Aerosol contents over the Indian Ocean varies from 1.4 to $68 \mu\text{g/m}^3$ air. It decreases southwards with the latitude and becomes zero close to Antarctica (Sen Gupta and Qasim, 1983a). From these values it can be inferred that the atmospheric flux of the elements is not very significant and the major transport route of pollutants in the Indian Ocean is through the riverine source.

Another important source of input is from the mining activities. Rejects and tailings from the mining operations carried out in coastal and nearshore regions add substantial quantities of heavy metals to the coastal environment.

Assessment of Possible Impacts of Pollutants on the Marine Environment

From the information summarized above it is clear that the data collected so far are quite fragmentary defying a clear understanding of the total pollution load in the Indian Ocean. However, the information also indicates that this region is not yet seriously affected by pollution. Localized problems, both short-term and long-term, do appear from time to time and their overall importance would vary from country to country.

However, the problem which is common to almost all the countries is oil pollution. Because of the transportation of a large volume of oil through the Indian Ocean, many areas are getting damaged. The worst affected ecosystems are the coral reefs and sandy beaches. Significant damages have already been noted on some of the atolls of Laccadives, coral reefs of the Andaman and Seychelles groups of islands, from Madagascar and also from the coastal regions of Kenya and Tanzania.

Other possible impacts can be expected to come from the disposal of untreated or little treated domestic sewage and industrial effluents. Continued washings of fertilizers, pesticides, herbicides and insecticides due to widespread agricultural practices in all the Indian Ocean countries can also pose significant problems.

But in the tropical and equatorial regions of the Indian Ocean, the tides are mostly of the semi-diurnal type with ranges varying from less than 1 m to more than 8 m. Tidal flushings twice a day, associated with biannual reversal of the direction of monsoon winds and the surface currents associated with smooth bottom topography

help in dispersing and diluting the pollutants and reducing the magnitude of their impact on the marine environment considerably.

Analysts of glacier samples from the Himalayas and ice and lake water samples from Antarctica (Table 7) have helped to establish background values for heavy metals in the northern and southern ends of the Indian Ocean (Sen Gupta and Qasim, 1983b). Utilising these it will be possible to maintain a watch on the Health of the Indian Ocean.

Acknowledgements

We thank all our colleagues who helped us by allowing us to use their published and unpublished data. We deeply appreciate the help of Mr. M. Wahidullah and his colleagues for drawing the figures and of Mrs. Vijayanti Date for secretarial assistance.

REFERENCES

1. Ansari, Z.A., A.H. Parulekar, S.N. Harkantra, and S.A. Nair, 1977, Shallow water macrobenthos along the central west coast of India. *Mahasagar—Bulletin of the National Institute of Oceanography*, 10, 123-127.
2. British Petroleum 1982, BP statistical review of the world energy. The British Petroleum Company Ltd., London, 33 pp.
3. Banse, K., 1968, Hydrography of the Arabian Sea shelf of India and Pakistan and effects on demersal fishes. *Deep-Sea Research*, 15, 45-79.
4. Braganca, A., and S. Sanzgiri, 1980, Concentration of a few trace metals in some coastal and offshore regions of the Bay of Bengal, *Indian Journal of Marine Sciences*, 9, 283-286.
5. Budyko, M.I., 1972, The water balance of the oceans, in : World water balance, Proc. of the Reading Symposium, 1970, IASH-UNESCO-EMO-Studies and reports in hydrology, 11, 1, 24-33.
6. Chester, R. and I.H. Stoner, 1974, The distribution of zinc, nickel, manganese, cadmium, copper and iron in some surface water from the world ocean. *Marine Chemistry*, 2, 17-32.
7. Curray, J.R. and D.C. Moore, 1971, Growth of the Bengal Deep-Sea fan and denudation in the Himalayas, *Bulletin of the Geological Society of America*, 82, 563-572.
8. Danielsson, L.G., 1980, Cadmium, cobalt, copper, iron, lead, nickel, zinc in Indian Ocean water, *Marine Chemistry*, 8, 199-215.
9. Deuser, W.G. 1971, Organic carbon budget of the Black Sea, *Deep-Sea Research*, 18, 995-1004.

10. Deuser, W.G., E.H. Ross, and Z.J. Mlodzinska, 1978. Evidence for the rate of denitrification in the Arabian Sea, *Deep-Sea Research*, 25, 431-455.
11. Dhargalkar, V.K., T.W. Kureishy, and M.V. Bhandare, 1977, Deposition of tar balls (oil residue) on beaches along the west coast of India. *Mahasagar—Bulletin of the National Institute of Oceanography*, 10, 103-108.
12. Dietrich, G. 1963, *General Oceanography*, interscience, New York, 588 pp, 13, Dietrich, G., and J. Ulrich, 1968, *Atlas Zur Ozeanographie*. Bibliographisches Institut, Mannheim, 76 pp.
13. Dietrich, G. 1973, The unique situation in the environment of the Indian Ocean, in : *The biology of the Indian Ocean*, editor B, Zeizschel, Springer Verlag, Berlin, 1-6.
14. Duing W., and W.D. Schwill, 1967, Ausbreitung und Vermischung des salzreichen wassers aus dem Roten Meer und aus dem Persischen Golf. *Meteor Forschungsergebnisse*, A3, 1-43.
15. Duing, W., 1970, The Monsoon regime of the currents in the Indian Ocean, International Indian Ocean Expedition, *Oceanogr., Monogr.*, 1, 1-68 East-West Centre Press, Honolulu.
16. EAMFRO, 1973, Annual report—East African Marine Fisheries Research Organization, Zanzibar, East African Community.
17. Emery, K.O., W.L. Orr, and S.C. Rittenberg, 1955, Nutrient budgets in the ocean, in : *Essays in the natural sciences in honour of Captain Allan Hancock*, University of Southern California Press, 299-309.
18. Ewing, M., S. Eittrheim, M. Truchan, and J.I. Ewing, 1969, Sediment distribution in the Indian Ocean. *Deep-Sea Research*, 16, 231-248.
19. FAO, 1978, *Yearbook of Fishery Statistics*, 45, FAO, Rome.
20. Fondekar, S.P. and R.S. Topgi, 1979, Trace analysis of pollutants in rainwater at Goa. *Mahasagar—Bulletin of the National Institute of Oceanography*, 12, 49-51.
21. Fondekar, S.P., R.S. Topgi, and R.J. Noronha, 1980, Dissolved, absorbed and adsorbed petroleum hydrocarbons from the central west coast of India, *Indian Journal of Marine Sciences*, 9, 286-289.
22. Ganesan, R., P.K. Shah, Z.R. Turel, and B.C. Haldar, 1980, Study of heavy elements (Cd, Hg and Se) in the environment around Bombay by radiochemical neutron activation analysis, Transaction 4th International Conference on Nuclear Methods in Environment and Environmental Research, Univ. of Missouri, Columbia, USA.
23. Harkantra, S.N., A. Nair, Z.A. Ansari, and A.H. Parulekar, 1980, Benthos of the shelf region along the west coast of India. *Indian Journal of Marine Sciences*, 9, 106-110.
24. Hartmann, M., H. Lange, S. Seibold, and E. Walger, 1971, Oberflächen—sedimente im Persischen Golf und Golf von Oman, I. Geologisch-Hydrologischer rahmen und erste sedimentologische ergebnisse, *Meteor Forschungsergebnisse*, C4, 1-76, Gebruder Borntraeger, Berlin.

25. Heezen, B.C., and M. Tharp, 1964, Physiographic diagram of the Indian Ocean, the Red Sea, the South China Sea, the Sulu Sea and Celebes Sea, Geological Society of America.
26. Holeman, J.N., 1968, The sediment yield of major rivers of the world. *Water Resources Research*, 4, 787-797.
27. Indian Ocean Biological Centre, 1968a, Maps on total zooplankton biomass in the Arabian Sea and the Bay of Bengal, in : *International Indian Ocean Expedition Plankton Atlas*, editor N.K. Pannikar, 1(1), NIO, CSIR, New Delhi.
28. Indian Ocean Biological Centre, 1968b, Maps on total zooplankton biomass in the Indian Ocean, in : *International Indian Ocean Expedition Plankton Atlas*, editor N.K. Panikkar, 1(2), NIO, CSIR, New Delhi.
29. Ivanenkov, V.N., and F.T. Gubin, 1960, Water masses and hydrochemistry of the western and southern parts of the Indian Ocean, *Trudy Morskii Gidrofiz. Inst., Akad. Nauk SSSR*, 22, 33-115.
30. Krey, J., and B. Babenerd, 1976, *Phytoplankton production, Atlas of the International Indian Ocean Expedition, IOC/UNESCO*, 70 pp.
31. Kureishy, T.W., M.D. George, and R. Sen Gupta, 1978, DDT concentration in zooplankton from the Arabian Sea, *Indian Journal of Marine Sciences*, 7, 54-55.
32. Kureishy, T.W., M.D. George, and R. Sen Gupta, 1979, Total mercury content in some marine fish from the Indian Ocean, *Marine Pollution Bulletin*, 10, 357-360.
33. Kureishy, T.W., S. Sanzgiri, and A.M. Braganca, 1981, Some heavy metals in fishes from the Andaman Sea, *Indian Journal of Marine Sciences*, 10, 303-307.
34. Levy, E.M., and A. Walton, 1976, High seas oil pollution-particulate petroleum residues in the North Atlantic, *Journal of the Fisheries Research Board of Canada*, 33, 2781-2791.
35. Lisitzin, A.P., 1971, Distribution of carbonate microfossils in suspension and in bottom sediments, in : *The micropaleontology of the oceans*, editors B.M. Funnel and W.R. Riedel, Cambridge University Press, London, 197-218.
36. McGill, D.A., 1973, Light and nutrients in the Indian Ocean, in : *The Biology of the Indian Ocean*, editor B. Zeitzschel, Springer Verlag, Berlin, 53-102.
37. McKenzie, D., and J.G. Sclator, 1971, The evolution of the Indian Ocean since the late Cretaceous, *Geophysical Journal of the Royal Astronomical Society*, London, 25, 437-528.
38. Mensveta, P., and R. Siriyong, 1977, Mercury content of several predacious fish in the Andaman Sea, *Marine Pollution Bulletin*, 8, 200-203.
39. Moore, W.S., and S. Krishnaswami, 1972, Coral growth rates using ^{228}Ra and ^{210}Pb , *Earth and Planetary Science Letters*, 15, 187-195.
40. National Institute of Oceanography, 1976, *Report on the Marine Environmental Monitoring and Marine Living Resources Assessment Programme for the Indian Ocean Region, Phase I—Survey of Institutional Capabilities*, Report submitted to UNEP (mimeo).

41. Naqvi, S.W.A., S.N. De Sousa, and C.V.G. Reddy, 1978, Relationship between nutrients and dissolved oxygen with special reference to water masses in western Bay of Bengal, *Indian Journal of Marine Sciences*, 7, 15-17.
42. Naqvi, S.W.A., R.J. Noronha, and C.V.G. Reddy, 1982, On denitrification in the Arabian Sea, *Deep-Sea Research*, 29, 459-469.
43. Parulekar, A.H. and Z.A. Ansari, 1981, Benthic macrofauna of the Andaman Sea. *Indian Journal of Marine Sciences*, 10, 280-284.
44. Prasad, R.R., S.K. Bannerjee, and P.V.R. Nair, 1970, A quantitative assessment of the potential fishery resources of the Indian Ocean and adjoining seas, *Indian Journal of Animal Sciences*, 48, 78-98.
45. Qasim, S.Z., 1977, Biological productivity of the Indian Ocean, *Indian Journal of Marine Sciences*, 6, 122-137.
46. Qasim, S.Z., 1982, Oceanography of the Northern Arabian Sea, *Deep-Sea Research*, 29, 1041-1068.
47. Qasim, S.Z. and R. Sen Gupta, 1980, Present status of marine pollution studies in India, in : *Management of Environment*, editor B. Patel, Wiley Eastern, New Delhi, 310-329.
48. Rama, and B.L.K. Somayajulu, 1972, Mercury in the sea food from the coast off Bombay, *Current Science*, 41, 207-208.
49. Qasim, S.Z. and R. Sen Gupta, 1983a, Marine pollution studies in India, in : *Water Pollution and Management Reviews, 1982*, editor C.K. Varshney, South Asian Publishers, New Delhi, 139-159.
50. Qasim, S.Z. and R. Sen Gupta, 1983b, Environmental Characteristics of the Ocean, in : *Encyclopedia of Environmental Science and Engineering*, editors J.R. Pfaffin and E.N. Ziegler, Gordon and Breach Science Publishers, New York, 294-309.
51. Rochford, D.J., 1964, Salinity maxima in the upper 1000 m of the North Indian Ocean, *Australian Journal of Marine and Freshwater Research*, 15, 1-24.
52. Ryther, J.H. and D.W. Menzel, 1965, On production, composition and distribution of organic matter in the western Arabian Sea, *Deep-Sea Research*, 12, 199-209.
53. Sadasivan, S., 1979, Trace elements in monsoon rains at Bombay and over the Arabian Sea. *Mausam*, 30 449-456.
54. Sano, A., N. Satoh, and N. Kubo, 1979, Particulate petroleum residues, tar balls, in the western Pacific, *Oceanographic Magazine, Japan*, 30, 47-54.
55. Sanzgiri, S., R. Sen Gupta and S.Y.S. Singbal, 1979, Total mercury concentrations in waters of the Laccadive Sea, *Indian Journal of Marine Sciences*, 8, 252-254.
56. Sanzgiri, S. and C. Moraes, 1979, Trace metals in the Laccadive Sea. *Indian Journal of Marine Sciences*, 8, 254-256.
57. Sanzgiri, S. and A. Braganca, 1981, Trace metals in the Andaman Sea. *Indian Journal of Marine Sciences*, 10, 238-240.

58. Sen Gupta, R., S.P. Fondekar, V.N. Sankaranarayanan and S.N. De Sousa, 1975, Chemical Oceanography of the Arabian Sea. Part I, Hydrochemical and hydrographical features of the northern basin, *Indian Journal of Marine Sciences*, 4, 136-140.
59. Sen Gupta, R., V.N. Sankaranarayanan, S.N. De Sousa and S.P. Fondekar, 1976a, Chemical oceanography of the Arabian Sea, Part III, Studies on nutrient fractions and stoichiometric relationships in the northern and the eastern basins, *Indian Journal of Marine Sciences*, 5, 58-71.
60. Sen Gupta, R., M.D. Rajagopal and S.Z. Qasim, 1976b, Relationship between dissolved oxygen and nutrients in northwestern Indian Ocean, *Indian Journal of Marine Sciences*, 5, 201-212.
61. Sen Gupta, R., S.N. De Sousa and T. Joseph, 1977, On nitrogen and phosphorus in Western Bay of Bengal, *Indian Journal of Marine Sciences*, 6, 107-110.
62. Sen Gupta, R., S. Naik, and S.Y.S. Singbal, 1978a, A study of fluoride, calcium and magnesium in the northern Indian Ocean, *Marine Chemistry*, 6, 125-141.
63. Sen Gupta, R., S.Y.S. Singbal, and S. Sanzgiri, 1978b, Atomic absorption analysis of a few trace metals in Arabian Sea waters, *Indian Journal of Marine Sciences*, 7, 295-299.
64. Sen Gupta, R., C. Moraes, T.W. Kureishy, V.N. Sankaranarayanan, T.K. Jana, S.W.A. Naqvi and M.D. Rajagopal, 1979, Chemical Oceanography of the Arabian Sea, Part IV, Laccadive Sea, *Indian Journal of Marine Sciences*, 8, 215-221.
65. Sen Gupta, R., S.Z. Qasim, S.P. Fondekar, and R.S. Topgi, 1980a, Dissolved petroleum hydrocarbons in some regions of the northern Indian Ocean, *Marine Pollution Bulletin*, 11, 65-68.
66. Sen Gupta, R., A. Braganca, R.J. Noronha and S.Y.S. Singbal, 1980, Chemical Oceanography of the Arabian Sea—Part V : Characteristics off the central west coast of India. *Indian Journal of Marine Sciences*, 9, 240-245.
67. Sen Gupta, R., and T.W. Kureishy, 1981, Present state of oil pollution in the northern Indian Ocean, *Marine Pollution Bulletin*, 12, 295-301.
68. Sen Gupta, R., and S.Z. Qasim, 1982, Oil pollution studies in northern Indian Ocean. *Petroleum Asia Journal*, 5, 33-37.
69. Sen Gupta, R. and S.Z. Qasim, 1983a, Measurement of aerosol particles along a section from 8°N latitude to Antarctica in the southwestern region of the Indian Ocean. *Scientific report of first Indian expedition to Antarctica*, Tech. publ. 1, 100-105.
70. Sen Gupta, R., and S.Z. Qasim, 1983b, Chemical studies on the ice shelf in a freshwater lake and in a polynya at Princess Astrid Coast, Dronning Maudland, Antarctica. *Scientific report of first Indian expedition to Antarctica*, Tech. publ. 1, 62-68.
71. Siddiquie, H.N., M. Veerayya, Ch. M. Rao, P.S.N. Murty and C.V.G. Reddy, 1976a, Deep-Sea drilling project site 219 on the Laccadive ridge. *Indian Journal of Marine Sciences*, 5, 18-34.

72. Siddiquie, H.N., and R.N. Sukeshwala, 1976b, Occurrence of Rhyolitic tuffs at deep-sea drilling project site 219 on the Laccadive ridge, *Journal of the Geological Society of India*, 17, 539-546.
73. Singbal, S.Y.S., S. Sanzgiri, and R. Sen Gupta, 1978, Total mercury concentrations in the Arabian Sea waters, *Indian Journal of Marine Sciences*, 7, 124-126.
74. Stoddart, D.R., 1972, Regional variation in Indian Ocean coral reefs, in : *Proceedings of the symposium on corals and coral reefs*. Mandapam Camp, India, editors C. Mukundan, and C.S.G. Pillai, The Marine Biological Association of India, Cochin, 155-174.
75. Tejam, B.M., and B.C. Halder, 1975, A preliminary survey of mercury in fish from Bombay and Thana environment, *Indian Journal of Environmental Health*, 17, 9-16.
76. Topgi, R.S., R.J. Noronha, and S.P. Fondekar, 1981, Dissolved petroleum hydrocarbons in the Andaman Sea, *Indian Journal of Marine Sciences*, 10, 241-242.
77. Topping, G., 1969, Concentrations of Mn, Co, Cu, & Fe in the northern Indian Ocean and Arabian Sea, *Journal of Marine Research*, 27, 318-326.
78. UNESCO, 1979, The mangrove ecosystem : human uses and management implications, *Unesco report in marine sciences*, 8 (mimeo).
79. Varadachari, V.V.R., and G.S. Sharma, 1967, Circulation of the surface waters in the north Indian Ocean, *Journal of the Indian Geophysical Union*, 4, 61-73.
80. Venkatarathnam, K., and J.D. Hayes, 1974, Sedimentation in the Indian Ocean, in : *Deep-Sea sediments—physical and mechanical properties*, editor A.L. Inderbitzen, Plenum Press, New York, 401-415.
81. Warren, B., Stommel, H., and J.C. Swallow, 1966, Water masses and patterns of flow in the Somali basin during the southwest monsoon of 1964, *Deep-Sea Research*, 13, 825-860.
82. Wooster, W.S., M.K. Schaeffer, and M.K. Robinson, 1967, *Atlas of the Arabian Sea for fishery oceanography*, Univ. of California, IMR ref. 67-12, 35 pp.
83. Wyrтки, K., 1971, *Oceanographic atlas of the International Indian Ocean Expedition*, National Science Foundation, U.S. Government Printing Office, Washington D.C., 531 pp.
84. Wyrтки, K., 1973, Physical oceanography of the Indian Ocean, in : *The biology of the Indian Ocean*, editor B. Zeitzschel, Springer Verlag, Berlin, 18-36.