

THE INDIAN OCEAN --- AN ENVIRONMENTAL OVERVIEW¹

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INTRODUCTION

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 unique study area.

In the present review, the Indian Ocean we discuss is an area bounded by 25°N and 30°S and 35°E and 98°E. Geographically, it is the area from 30°S latitude to the Gulf of Oman and the head of the Bay of Bengal and from the East African coast to the coastlines of Burma, Thailand and Malaysia (excluding the Strait of Malacca) (Fig. 1). In this region of the Indian Ocean, there are 19 countries, comprising a total area of 9.6×10^6 km². They are inhabited by about 1220 million people, with an average population density of 127/km². Thus, an average 22.5% of the world population lives in 18.6% of the total land area. The 8 countries in the East African region (of which 4 are island countries), however, have a population density of only 16.5/km².

OCEANOGRAPHIC FEATURES

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

PHYSICAL

The Indian Ocean occupies an area of 74.92×10^6 km² including the marginal seas (DIETRICH, 1963), representing 20.8% of the total world oceans. Average depth is 3873 m. According to BUDYKO (1972), the Indian Ocean has a negative water balance: Annually it receives 6000 km³ of river runoff and 88,000 km³ of precipitation while its evaporation is 103,000 km³.

However, there are some parts of the Indian Ocean in which the water balance is positive. One such area is the Bay of Bengal in the northeast, which receives an annual precipitation of 11,000 km³ and a runoff of 1730 km³. Assuming the limit of dilution at 25 m depth, these volumes or precipitation and runoff would dilute the surface water by about 5% (SEN GUPTA et al., 1978a). The Arabian Sea, in the northwestern part of the Indian Ocean, in contrast, is a region of negative water balance. It receives annually a precipitation of 10,000 km³ and runoff of 525 km³ from the rivers of India and Pakistan. Thus, these two areas, although covering 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 receive 9% of the global river runoff.

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The northern boundary of the Indian Ocean receives waters of high salinity from the Arabian 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 subsurface water masses in the Indian Ocean that originate from the north. The presence of the Gulf and the Red Sea water masses has been traced to the equator and into the western part of the Bay of Bengal. The Gulf water has a characteristic σ_t of 26.5 that can be identified from a depth range 100 to 300 m in the Arabian Sea to about 500 m in the equatorial Indian Ocean (Fig. 2). The water from the Red Sea can be traced by its characteristic σ_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).

Two other surface water masses are formed in the northern Indian Ocean. One is a high salinity surface water in the northern and central Arabian Sea formed due to excess of evaporation; it has a σ_t of 25 (ROCHFORD, 1964) and occurs to a depth of about 125 m. Due to an excess of precipitation and a very large volume of runoff, a low salinity surface water mass forms 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 with a σ_t of 27.6 as the North Indian Ocean Deep Water, and the water mass below 3000 m with a σ_t 27.8 as the North Indian Ocean Bottom Water (Fig. 2). These two water masses are formed as a result of mixing of the Antarctic Deep and Circumpolar water masses. According to WOOSTER et al. (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, spreading out in both the central and eastern basins. They can be identified by their characteristic σ_t values. In addition to the water masses, broadly classified above, there are several other water masses formed due to mixing which are not described here due to limited space.

✓The Indian Ocean has an N-S asymmetric shape due to the presence of the Asian continent. The result is that this ocean is separated from the deep-reaching vertical convection areas of the northern hemisphere. Such an asymmetric configuration leads to a weak circulation and poor renewal in the deep northern Indian Ocean. In addition, it is strongly influenced up to 10°S by the characteristic atmospheric monsoon circulation (DIETRICH, 1973): Surface circulation in the north 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 for the study of ocean-atmosphere interactions.

During the northeast monsoon (November-April) the oceanic circulation north of the equator remains moderately strong and is east to west. It penetrates beyond the thermocline. Due to 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 the enormous volume of river runoff probably compensates for the weak upwelling of the northeastern region.

During the southwest monsoon, the South Equatorial current becomes stronger and subsequently forms the East African Coastal Current. It flows northward, ending up as the Somali Current which frequently attains velocities as strong as those of other western boundary currents, e.g., the Gulf Stream or the Kuroshio (WARREN et al., 1966). The monsoon current, the South Equatorial Current and the Somali Current form 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 subsurface waters less than 20°C reach the sea surface (WARREN et al., 1966).

Strong winds also blow 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 no strong current develops. During the southwest monsoon season 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 interpreted 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 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.

CHEMICAL

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

Because of a sluggish circulation and weak renewal, a thick layer with 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 very often is less than 0.5 ml l⁻¹. Off the Indian coast values lower than even 0.05 ml l⁻¹ have 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 Indian Ocean is marked by high PO₄⁻³ - P contents, sometimes associated with low oxygen concentrations, due to upwelling. Phosphate concentrations in the region of Somali upwelling reach values greater than 1 μ mol l⁻¹ at the surface. For the southwestern Indian Ocean the range is from 0.25 to 0.54 μ mol l⁻¹, increasing with depth to a maximum between 300 and 500 m. Concentrations remain more or less constant throughout the rest of the water column, decreasing slightly near the bottom.

Values for NO⁻³ - N indicate similar features, with higher values at the surface during the upwelling period. Generally, NO⁻³ - N concentrations range from 1 μ mol l⁻¹ at the surface to about 50 μ mol l⁻¹ between 3000 and 4000 m. But during the periods of high photosynthetic productivity, the surface values quite frequently reach zero.

Marked changes in nutrient concentrations occur at 10°S. The monsoon gyre in the northern Indian Ocean is marked by high PO₄⁻³ - P concentrations, and within this region the concentrations range from less than 0.4 μ mol l⁻¹ to more than 1 μ mol l⁻¹. In the areas of the sub-tropical gyre nutrient values are very low.

RYTHER and MENZEL (1965) concluded that 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.

Subsequent to the 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, 1976a and b, 1977, 1979, 1980b; NAQVI et al., 1978, 1982; DEUSER et al., 1978). These studies have revealed that about one-third of the dissolved nitrate-nitrogen is lost during denitrification in the oxygen-poor layer of the northern Arabian Sea; this process can be traced to 2°N. Occasionally, two nitrite-nitrogen maxima and two oxygen minima are observed in this region. The depths of the maximum intensity of denitrification invariably coincide with the secondary nitrite maxima (Fig. 3). The rate of denitrification is 200 g m⁻² in the waters of the northernmost part of the Arabian Sea, where renewal of deeper water is very slow due to the sluggish movement of water (QASIM, 1982). The rate is 70 g m⁻² at 15°N (SEN GUPTA et al., 1980b), and 45 g m⁻² at 12°N (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), 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 rate of outflow from the Gulf of about 3 x 10³ km³ yr⁻¹.

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 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 in the other two oceans. Silicate values can be used to identify different water masses by plotting them against the sigma-t values. This also has 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).

BIOLOGICAL

Several atlases on the phytoplankton and zooplankton production in the Indian Ocean were published based on IOE data (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 were estimated by QASIM (1977). The gist of the information is presented below.

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

The range in column production varies from 0.001 to 6.5 g C m⁻² day⁻¹. Areas of high productivity lie mostly in the coastal and upwelling zones. These include the Gulf of Oman, the mouth of the Indus River, Saudi Arabian waters, Somalian and Mozambique coasts, southwest coast of India, the mouth of the River Ganga, the Burma coast, and off northern Sumatra Java (Fig. 4). The average production in the coastal areas works out to be 485 g C m⁻² yr⁻¹ as compared to the offshore average of 229 g C m⁻² yr⁻¹. Total photosynthetic productivity in the Indian Ocean has been found to range from 3 to 6 x 10⁹ tonnes C yr⁻¹ with an average of 4.5 x 10⁹ tonnes C yr⁻¹ or 258 mg C m⁻² day⁻¹.

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 is 1.1 x 10⁹ tonnes C yr⁻¹, while in the Bay of Bengal it is 0.4 x 10⁹ tonnes C yr⁻¹. This means that these two areas account for about one-third of the total photosynthetic productivity of the Indian Ocean although together they occupy only about 14% of the total area. There is, however, a qualitative difference in the productivity of these two areas. The surface productivity (1 m depth) in the Bay of Bengal is 4.9 tonnes C km⁻² yr⁻¹ while in the Arabian Sea it is 3.9 tonnes C km⁻² yr⁻¹. This anomalous situation between column and surface productivity has been attributed to greater cloud cover and higher surface nutrient load, particularly nitrate-nitrogen, in the Bay of Bengal (QASIM, 1977).

Zooplankton biomass in the Indian Ocean varies from 15 to 50 ml m⁻². The total zooplankton biomass in the Indian Ocean has been estimated to be 5.2 x 10⁸ tonnes yr⁻¹ (PRASAD et al., 1970), and secondary production works out to 69.3 x 10⁶ tonnes C yr⁻¹. Areas of high abundance mostly coincide with high photosynthetic productivity.

Benthic production in the Indian Ocean predictably decreases with water depth. The density of meiofauna, however, is greater than that of the macrofauna in deeper waters. Benthic population is larger in the areas of high productivity. Average benthic productivity in the Arabian Sea to a depth of 2100 m is 1.8 g C m⁻² yr⁻¹, while in the Bay of Bengal (to a depth of 1870 m) and the Andaman Sea (to a depth of 1820 m) productivities are 0.5 and 1.2 g C m⁻² yr⁻¹, 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 x 10⁶ 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 20.8% of the world oceans area, yields only 2.8% of the global fish catch. The potential yield of the Indian Ocean has been estimated as 14.2 x 10⁶ tonnes yr⁻¹ (QASIM, 1977). Therefore, there is much scope for increasing fish production of the Indian Ocean by increasing the effort.

GEOLOGICAL

Because of its asymmetric shape, the Indian Ocean is separated from the deep-reaching vertical convection areas of the northern hemisphere (DIETRICH and ULRICH, 1968). Recent geophysical investigations indicate that the Indian Ocean is the most complex of the three major oceans in terms of its history of formation, and hence its physiography, probably because of this asymmetric configuration (McKENZIE and SCLATER, 1971). Measurements of its magnetic field show that the floor of this ocean is spreading at the rate of 2 cm/year and implies that the Indian Ocean is about 10^8 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 (Fig. 5) shown by HEEZEN and THARP (1964). Microcontinents and meridional aseismic ridges, e.g., the Ninety-East Ridge and the Chagos-Laccadive Plateau, are unique to the Indian Ocean (HEEZEN and THARP, 1964). Although massive, these features are relatively smooth-surfaced blocks and stand 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 between the topographic highs. Sediment cones and abyssal plains, with sediment thicknesses 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 and MOORE, 1971). In the high southern latitudes near the polar front, smooth, 'swale' topography with moderate sediment thickness appears as a result of high productivity of the Antarctic Ocean, while in other areas, and especially on topographic highs, the sediment cover 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 character 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, about 16×10^8 tonnes, is added by the river systems draining the Indian sub-continent.

In terms of areal extent, the most extensive sedimentary facies in the Indian Ocean is calcareous sediment which dominates the Mid-Indian Ridge and other more shallower areas not influenced by terrigenous influx or 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). Other sedimentary facies include: 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 and 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 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 for 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 some of the problems are chronic in some countries, they are relatively simple in others. In this review, however, no attempt has been made to differentiate them.

DOMESTIC SEWAGE AND INDUSTRIAL EFFLUENTS

Due to increasing urbanization and industrialization throughout the region, the volume of sewage and industrial waste is increasing constantly, and, as a result, both contribute directly and indirectly to the degradation of the adjoining seas. Sewage and industrial wastes in these countries, untreated or partially treated, are discharged into the rivers and seas. Many countries have large rivers, but because of increased human activities, many of these rivers have become badly polluted. In India, for example, only 42 cities with populations 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 often are found on the beaches and in coastal waters.

It has been calculated that 27 million people in East Africa live along the coastline and are directly or indirectly dependent on the sea for their livelihood. Calculating the consumption of water at 60 litres/capita/day, this population can be expected to generate $585 \times 10^6 \text{ m}^3$ sewage and effluents per year. The same population will generate 7.8×10^6 tonnes of solid waste (at 0.8 kg capita/day).

Only 17% of a population of 3.8 million living in the coastal cities in eastern Africa are sewered (UNEP, 1982a, b). Representative values of this sewage before disposal indicate high BOD and COD loads, along with a high concentration of suspended solids. The solid wastes generated are used mostly for landfill. Consequently, the risk of contamination of ground water from the landfill leachate is fairly high. Representative analysis of leachates from Kenya indicate high values for BOD, alkalinity and total hardness. Assuming that the industrial effluents would be about 10% of the sewage, the total quantity which is discharged in the coastal marine environment, in mostly pre-treated form, would come to $59 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$. The sources of these effluents are slaughter houses, breweries, distilleries, textile mills, saw mills, refineries, fertilizer plants, pulp and paper mills, etc. Representative analysis of the industrial effluents from Tanzania indicate high BOD and COD loads.

Concentrations of toxic metals, such as Hg, Cd and Pb, in plankton and fish are still much lower than the acceptable maxima in many industrialized countries.

AGRICULTURAL WASTES

Fertilisers, pesticides and insecticides are abundantly used in developing countries for agriculture, pest control and vector control. The quantities of pesticides and insecticides used every year vary from 45,000 tonnes in India to 3.5 tonnes in Bangladesh (NIO, 1976). In many countries, however, organochlorine pesticides are either prohibited or gradually are 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 concentrations ranging from 0.05—3.21 ppm wet weight (KUREISHY et al., 1978).

Use of these harmful organochlorine and organomercurial pesticides has been totally banned in all the industrial countries of the world. But their total production has not been reduced; rather their manufacture has increased, suggesting that soon there will be a 'southward' tilt of the concentration of organochlorine and organomercurial pesticides in the marine environment.

RADIOACTIVE AND THERMAL WASTES

In countries in 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 discarded according to strict international conventions. However, their heat generation can pose 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, and as such they cannot withstand a large increase in ambient temperature. Release of hot salty water, when coupled with the wind system, can alter the current and mixing patterns in local areas. This is more probable in tropical areas where the range of the semi-diurnal tides is quite high.

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 around Sri Lanka across the southern Bay of Bengal and through the Malacca Strait to Far East and Japan (Fig. 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, makes the northern Indian Ocean very vulnerable to oil pollution.

Sources of oil pollution include 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 is about 3700 tonnes, while along the tanker route across the southern Bay of Bengal the tar amounts 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.

The East African countries together import 6.55 mt of oil per year, and oil pollution is a chronic problem in countries of this region (NIO, 1980) (Fig. 7). It has been estimated that the total oil spill from tanker traffic, harbour operations, coastal industries, etc., comes to about 33,000 tonnes per year in East Africa (UNEP, 1982c). Figure 6 suggests that tanker traffic, from the Gulf to South Africa, represents the single largest source of oil pollution.

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 spoiled the beauty of the beaches, leading to contamination of the environment and generation of hydrogen sulphide in the water.

CORAL REEFS AND MANGROVES

Coral reefs and mangroves occur widely in most all Indian Ocean coastal areas. 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:

Coral Reefs

Coral reefs of the tropical Indian Ocean include fringing and barrier reefs; sea-level atolls; and elevated reefs (STODDART, 1972). They occur along the NW and SE coasts of India, the 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 ages of more than 2000 years (STODDART, 1972). The growth rate of corals in the Atlantic has been found to be $0.15-0.5 \text{ cm yr}^{-1}$ 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 Kavaratti reef in the Laccadives; reefs 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 has destroyed some of the coral reefs on Mahe Island in the Seychelles.

Mangroves

Mangroves, which occur along NE coast of India, Bangladesh, Malaysia, Sri Lanka, Mauritius, Seychelles and Indonesia, constitute an important resource in the region as they serve as 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 levels and the direction of flow. Mangroves constitute a significant portion of the coastal wetland in many countries and a fairly large percentage of human population 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 the 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 in coastal areas during cyclones.

SILTATION

As noted above, the Indian Ocean receives annually 34×10^8 tonnes of suspended sediment (HOLEMAN, 1968), half of which comes from the rivers draining the Indian sub-continent. This quantity is increasing due to human activities, such as mining, 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 suggested in many countries, not much direct evidence has been obtained on the influence of siltation on marine and estuarine fisheries.

RESEARCH AND MONITORING ACTIVITIES

Monitoring and research on marine pollution are fast developing activities in many countries of the Indian Ocean region. Baseline surveys on almost all potential pollutants in the marine environment are underway, and a fairly good data base has been built up. These data mostly concern environmental conditions in the coastal and nearshore regions and also on some parts of the open areas of the Arabian Sea, the Bay of Bengal, and adjacent areas of the Laccadive and the Andaman Islands. Several reviews have been published in recent years (QASIM and SEN GUPTA, 1980, 1983a and b). The following details have been extracted from these publications combined with data collected subsequently.

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). Plotted in 5°-squares (Fig. 6), the percentage of oil sightings ranged from 51 to 96. Even in areas away from tanker and trade routes, the percentage of oil sightings was almost of a similar order. Fortunately, the occurrence of tanker disasters has not been very significant along these routes so far, and most of the oil released in this region comes mainly from the ballast and bilge washings.

Observations on the floating petroleum residues from the Indian Ocean region are presented in Table 1. As expected the concentrations and variations in time and are fairly high occasionally along the tanker routes. In the Arabian Sea concentrations range from 0 to 6.0 mg m⁻², with a mean of 0.59 mg m⁻². The range along the Bay of Bengal tanker route varies from 0 to 69.75 mg m⁻², with a mean of 1.52 mg m⁻². This suggests that the tanker route in the Bay of Bengal is relatively more polluted than that in the Arabian Sea.

Observations in March 1981 along the eastern 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 m⁻² with an average of 12.7 mg m⁻² 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 eastern tanker route in 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 the 3700 and 1100 tonnes quoted previously.

Accumulation of floating tar is entirely dependent on surface currents. In areas of strong surface currents, e.g. the Gulf Stream and Kuroshio, heavy accumulation of tar particles has been observed. The observed concentration in the North Atlantic ranges from 0.12—0.64 mg m⁻², with a maximum of 91.8 mg m⁻² (LEVY and WALTON, 1976). Accumulations in the northwestern Pacific range from 0.02—13.3 mg m⁻² (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 assume 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 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 are almost uniform. However, some seasonal variations may be due to differences in the intensity of tanker traffic from month to month and because of changes in meteorological conditions.

The average concentrations of dissolved petroleum hydrocarbons in the upper 20 m of the tanker routes in the Arabian Sea and the Bay of Bengal are 42.8 and 28.2 $\mu\text{g kg}^{-1}$ respectively. Calculating the volumes in the upper 20 m from the total areas mentioned earlier, the quantity of petroleum hydrocarbons 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 along the Bay of Bengal tanker route. Summing up of all the values in Table 1 results in Figure 6, depicting the dissolved petroleum residues in the northern Indian Ocean.

All available data on dissolved/dispersed petroleum hydrocarbons in the upper 20 m of the Northern Indian ocean (Table 1A) indicate a general decreasing trend of oil transport from the Middle East countries, particularly along the west going tanker route. Consequently, the volume of tanker traffic has also reduced considerably. Due to the reduction in traffic, an apparent reduction in the oil pollution can be deduced from the data for the tanker routes across the Arabian Sea and the Bay of Bengal. The reduction was sharp from 1982 onwards in the Arabian Sea and from 1981 onwards in the Bay of Bengal. Thereafter, the conditions appear to have stabilized in both the areas. However, the net reduction in transport is more significant for the west-going tanker route than that for the east-going one. In fact, more oil was transported to the eastern hemisphere from 1984 as compared to the western hemisphere.

Almost all of the countries of this region are signatories to the 1973 MARPOL Convention of IMO and the 1978 protocol. Many have already ratified the accords. These have resulted in the establishment of reception facilities for oily bilges, ballasts and sludges at almost all the major ports. With the establishment of such facilities at all the ports, oil pollution in the Northern Indian Ocean can be expected to be reduced in the future.

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 concentrations were found to range from 19.5—83.3 $\mu\text{g g}^{-1}$, while in the sediments the range was 4.8—8.5 $\mu\text{g g}^{-1}$, both on dry weight basis.

Deposition of tar-like residues on the beaches is more or less a chronic problem in almost all countries bordering the Indian Ocean. However, this is a seasonal phenomenon, 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} (DHARGALKAR et al., 1977). Observations on the beaches in Kenya give a range of values of 20 to 2400 $\text{g } 100 \text{ m}^{-2}$, with a peak value of 1386 g m^{-2} (EAMFRO, 1973). Tar lumps as heavy as 16 kg have been observed on Kenyan beaches.

HEAVY METALS OTHER THAN MERCURY

In Water

Some data on the dissolved concentrations of heavy metals are available from the Indian Ocean region (Table 2). The large ranges may be due to different analytical techniques used as well as horizontal and vertical variations. 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 $\mu\text{g l}^{-1}$. Except for copper, all the higher values are either from coastal India or off the coasts of oceanic islands. The higher ranges of iron, manganese and nickel are from around the Laccadive Islands; high cadmium and lead are from around Andaman Islands; high zinc occurs off Bombay, and high cobalt off the river mouths in the Bay of Bengal. An exceptionally high value of cadmium, 80 $\mu\text{g l}^{-1}$, was recorded in the polluted coastal waters off the city of Bombay (GANESAN et al., 1980).

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 give 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. 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). It can be seen from Table 3 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 (*Neothunus 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.

MERCURY

Because of its extreme toxicity and very harmful nature to human beings, mercury warrants special discussion. Unfortunately, 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.

In Water

Mercury concentrations in dissolved form are normally found at the nannogram levels. Their sources are mostly industrial effluents, but some contribution also can be expected from weathering, leaching and atmospheric flux from deposits of 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 $\mu\text{g l}^{-1}$ in the surface waters, 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 $\mu\text{g l}^{-1}$. 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).

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 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 probably assimilated by fishes through other pathways. Mercury concentrations in the muscles of sharks and skipjack tuna are particularly high (Table 3). Concentrations of non-essential heavy metals (Hg, Cd and Pb) in different tissues of the fishes from the northern Indian Ocean (Table 4) indicate highest occurrences 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. Mercury contents in the muscles of several commercially important fishes from inshore regions and from a polluted creek in and around the city of Bombay range from 0.04—0.57 ppm on a fresh weight basis (TEJAM and HALDAR, 1975; RAMA and SOMAYAJULU, 1972). However, the concentration of the same metal in crab muscles and sediments analysed in 1980, 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. A few fishes around Seychelles have been observed to contain 1-2 mg kg^{-1} mercury, much above the maximum permissible limit of 0.5—1 mg kg^{-1} in many countries.

PESTICIDES

Some analyses of pesticide residues in zooplankton in the Arabian Sea and in sediments along the east coast of India have been carried out (KUREISHY et al., 1978; KANNAN and SEN GUPTA, 1987; SARKAR and SEN GUPTA, unpublished). Concentrations in zooplankton only for DDT and its isomers, represented as t-DDT, (Figure 7) decrease from nearshore to offshore regions indicating the land origin of the pesticides. Measurements of t-DDT in the surface waters of the Arabian Sea and in the air over it indicate a northward increase from the equator (TANABE and TATSUKAWA, 1980), confirming the land origin of these residues.

A recent study of pesticides residues in the sediments along the east coast of India (SARKAR and SEN GUPTA, unpublished) indicates that, apart from DDT and its isomers, residues of Gamma BHC, Aldrine and Dieldrine also are present at a number of places. Their individual concentrations are higher than t-DDT at a few stations. Diagrammatic representation of these values indicates higher concentrations mainly at the river mouths (Fig. 8). Once again, this would indicate the land origin of the pesticides.

The estimated annual amount of pesticides and insecticides used in India is about 55,000 tonnes (Table 6). Recent estimates indicate that about 3,000 tonnes of pesticides are imported into Bangladesh every year (UNEP, 1986). Most of the countries in this region are mainly agricultural and considerable quantities of pesticides and insecticides also can be expected to be used by them. It is commonly believed that about 25% of these ultimately end up in the sea. The cumulative effect of the non-degradable pesticides over the years can be considerable in the coastal marine sediments.

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 perhaps can be obtained by extrapolating the data given in Table 6 to population density.

Most of cations and anions added to the oceans are adsorbed on to clay and silt particles. Considering the enormous amount of sediment added annually to the Indian Ocean, i.e., 34×10^8 tonnes (HOLEMAN, 1968), river-borne sediment 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 are: 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 $\mu\text{g l}^{-1}$ (SADASIVAN, 1979); Fe 4.3, Co 0.1, Ni 0.1, Cu 6.8, Zn 13.3, Pb 21.5 all in $\mu\text{g l}^{-1}$ (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 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 too fragmentary to allow a clear understanding of the total pollution problem in the Indian Ocean. However, the information suggests 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 varies from country to country.

However, the problem 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 being damaged. The worst affected ecosystems probably will be coral reefs and sandy beaches. Significant damage already has been noted on some of the atolls of Laccadives, coral reefs of the Andaman and Seychelles islands, Madagascar, and also from 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 also can pose significant problems.

But in the tropical and equatorial regions of the Indian Ocean, the tides are mostly semi-diurnal, 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.

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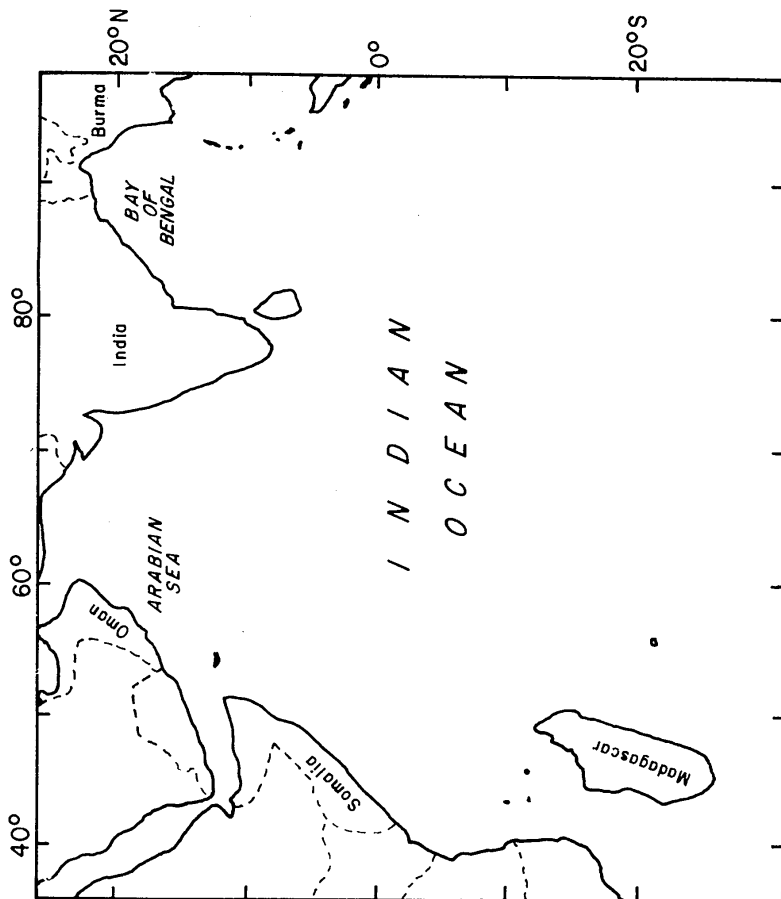


Figure 1. The Indian Ocean as defined in this paper.

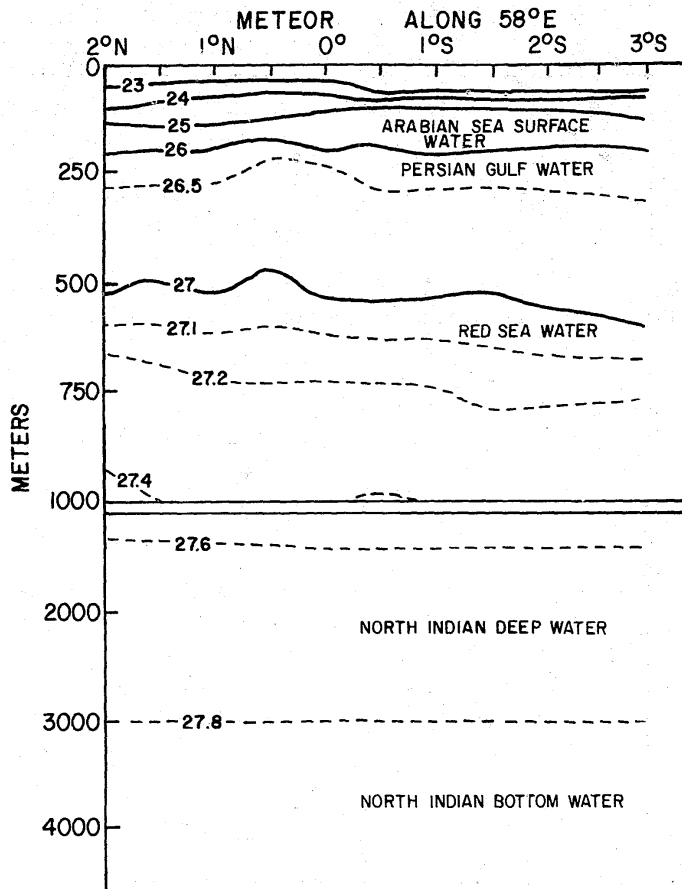


Figure 2. Water masses in a cross-section at 58°E longitude in the Indian Ocean (From METEOR data 1964/65).

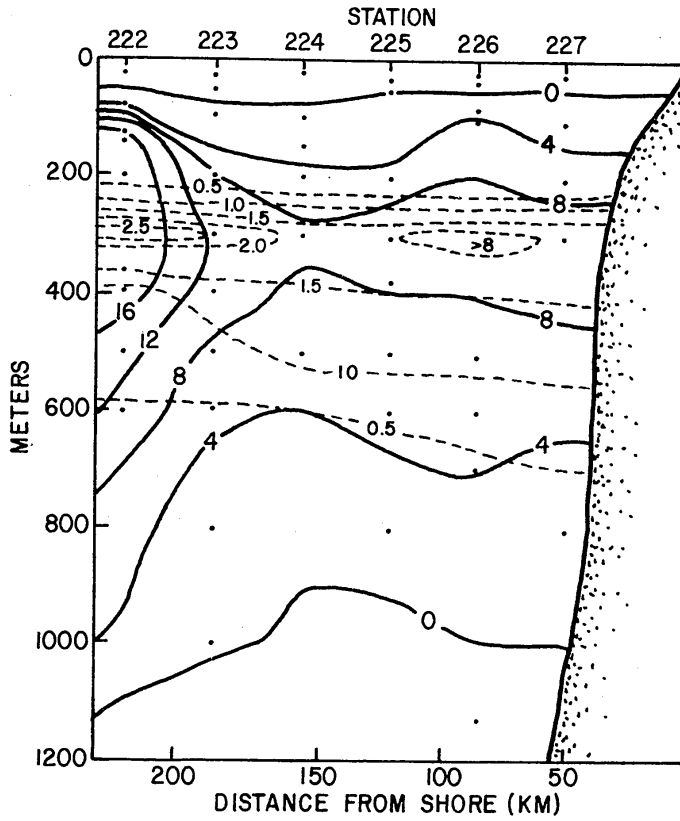


Figure 3. Calculated nitrate anomaly and nitrite distributions for METEOR (1964/65) stations 222-227 in the northeastern Indian Ocean. Nitrate anomaly (continuous lines) and dissolved nitrite (broken lines). Concentrations are in $\mu\text{g-at l}^{-1}$

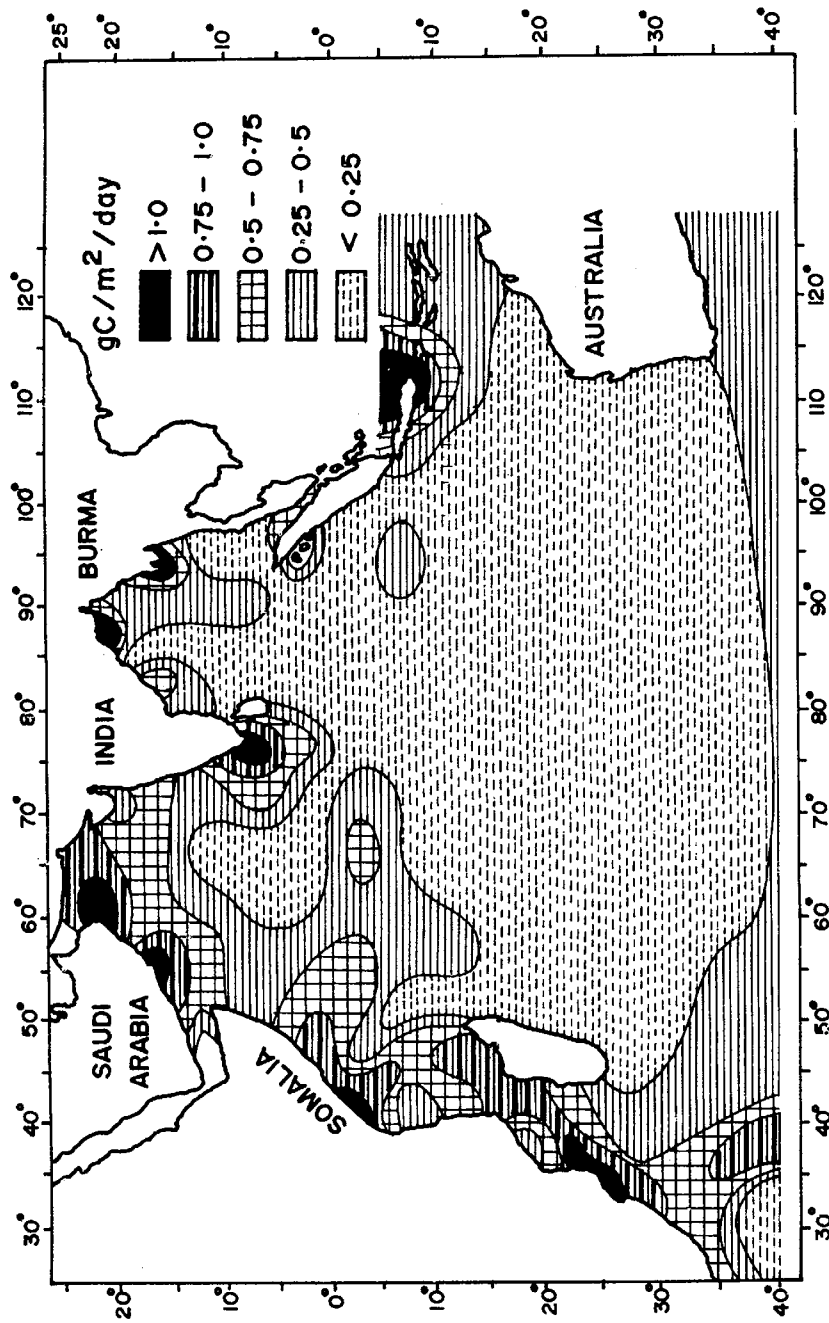


Figure 4. Primary productivity in the Indian Ocean (From QASIM, 1977).

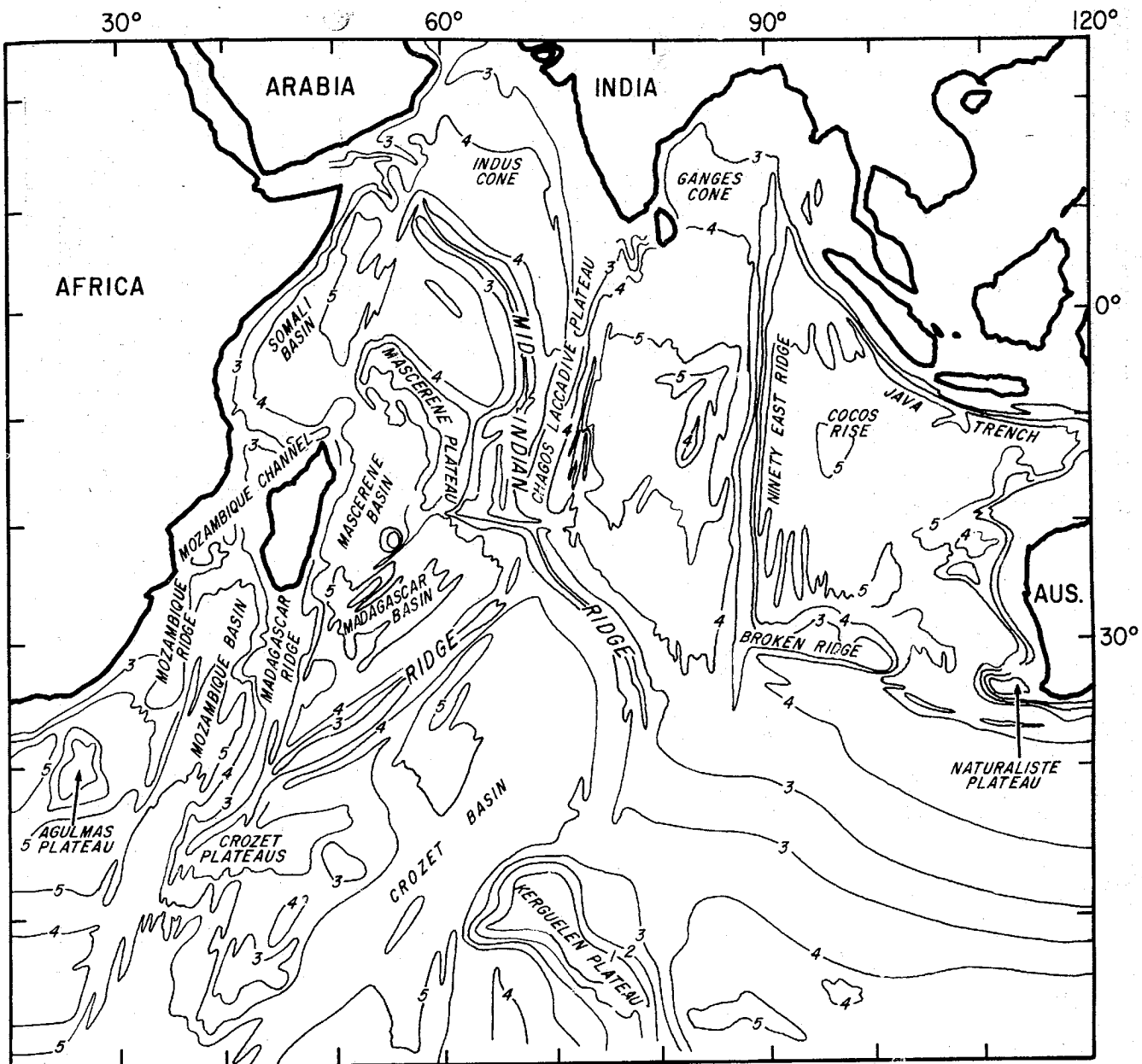


Figure 5. The Indian Ocean floor (from HEEZEN and THARP, 1964).

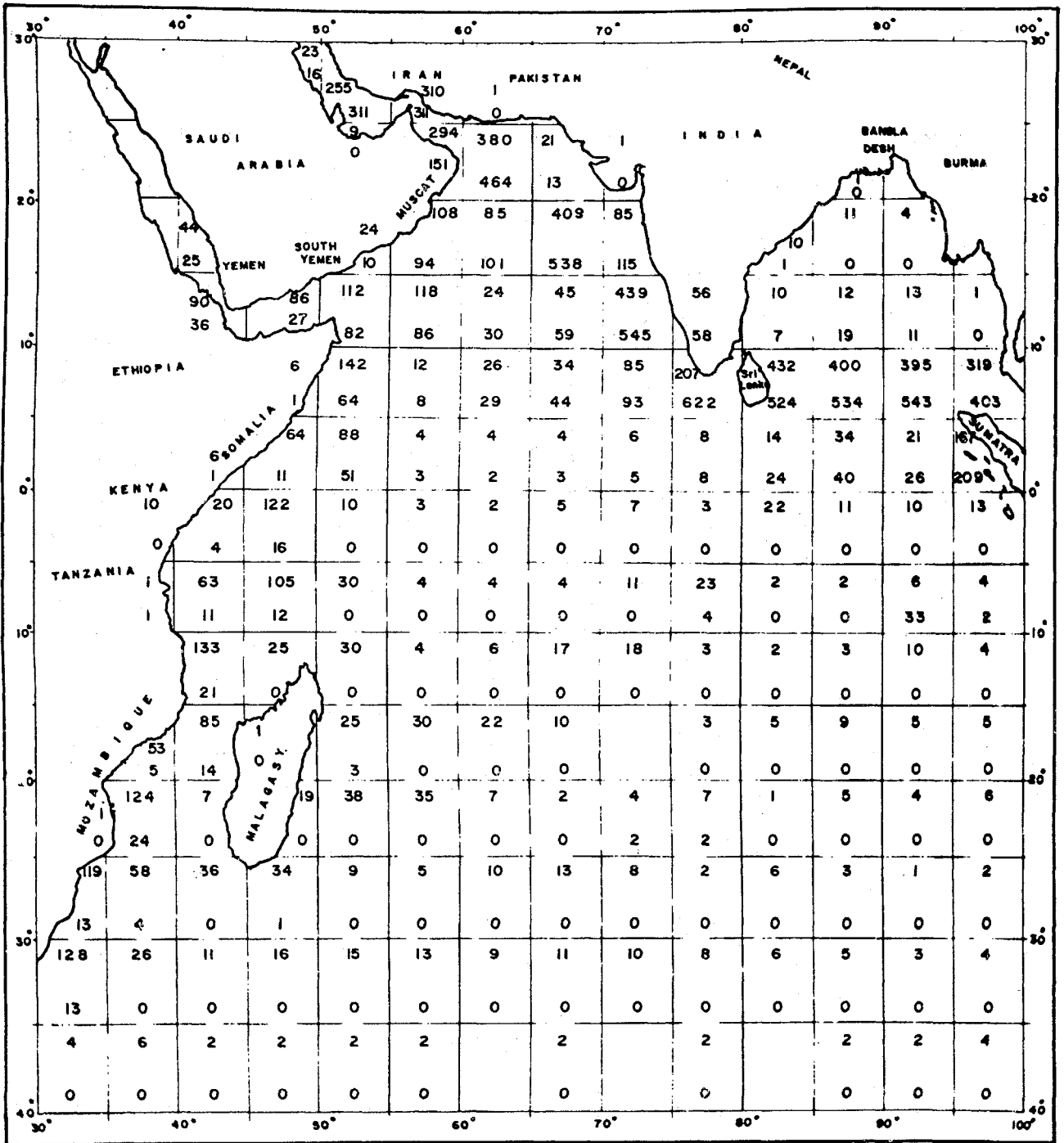


Figure 6. Observations of oil slicks and other floating pollutants, every 50-square in the Indian Ocean. Upper numbers indicate number of sightings; lower numbers indicate occasions of the absence of oil slicks.

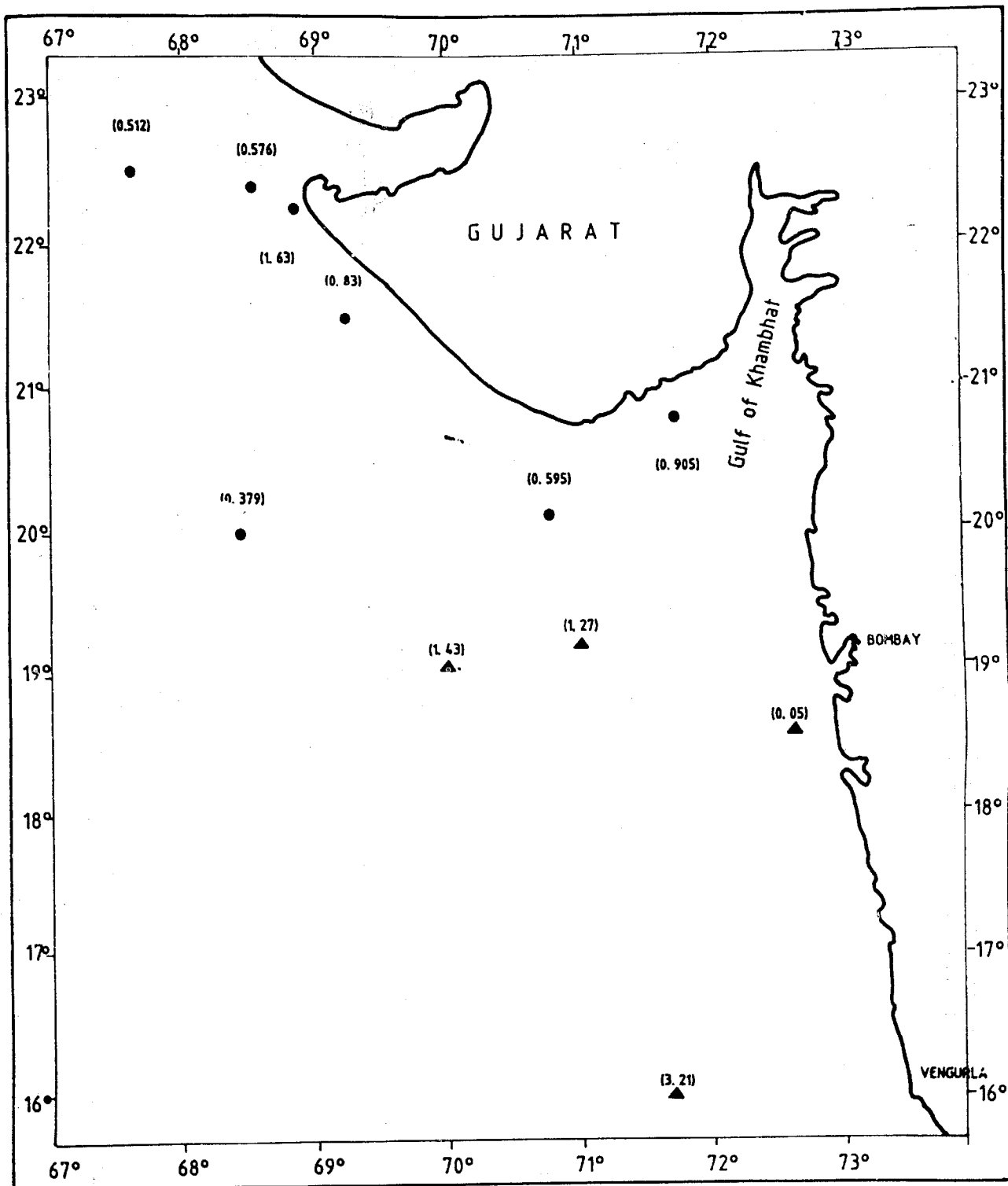


Figure 7. t-DDT in zooplankton of the eastern Arabian Sea. Closed triangles are observations in 1978. Closed circles indicate results of observations in 1985 (from KANNAN and SEN GUPTA, 1987).

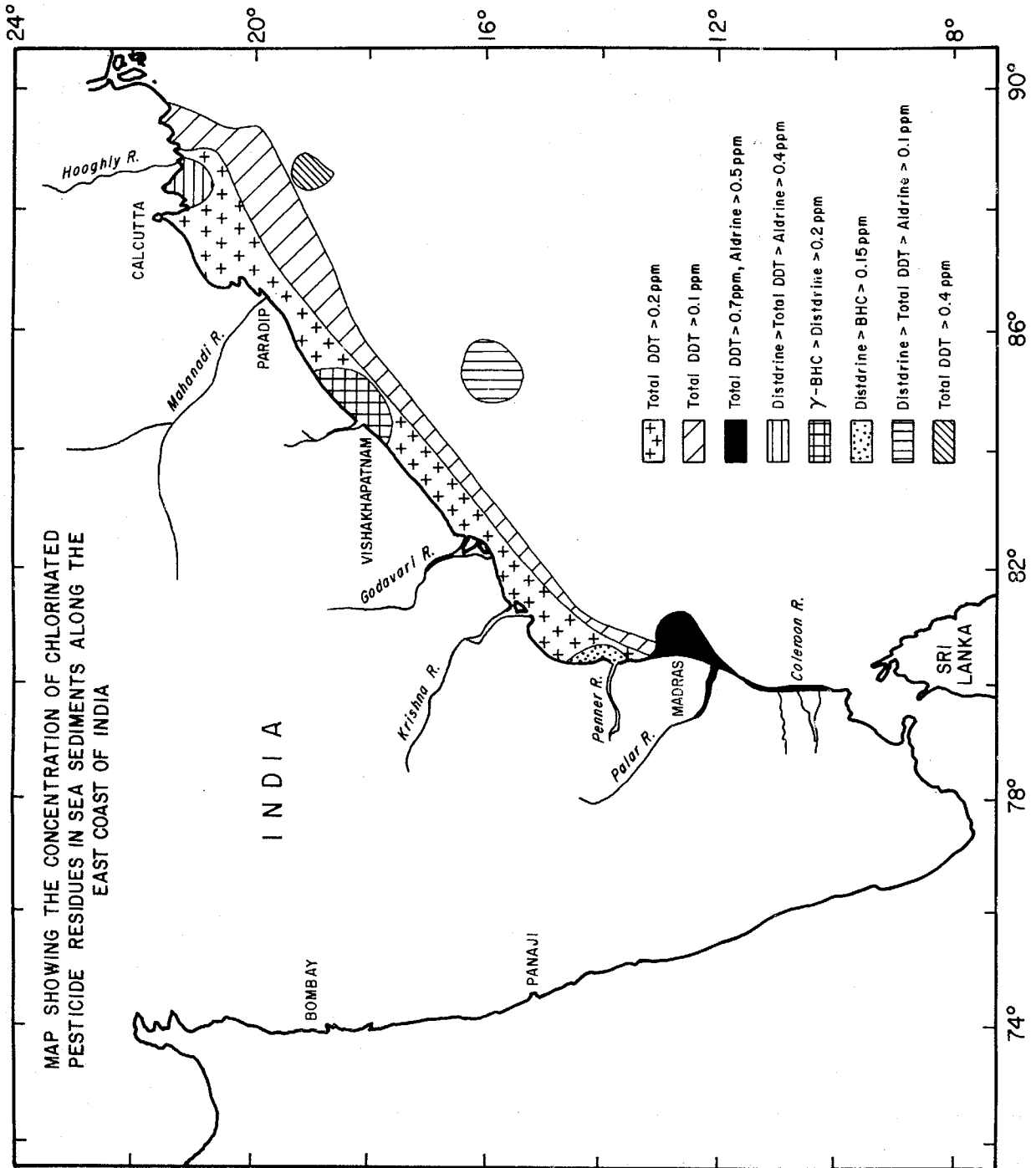


Figure 8. Chlorinated pesticide residues in sediments along the east coast of India (from SARKAR and SEN GUPTA, unpublished).

Table 1. Dispersed hydrocarbons and particulate petroleum residues (tar balls) in the Arabian Sea and Bay of Bengal (SEN GUPTA et al., 1980a; FONDEKAR et al., 1980; SEN GUPTA and KUREISHY, 1981; TOPGI et al., 1981).

| | | Dissolved/Dispersed hydrocarbons ($\mu\text{g kg}^{-1}$) | | | |
|---|-----------|--|--------------|---------------|-----------------------|
| | | Arabian Sea | | Bay of Bengal | |
| 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) |
| | | | | 0— 2.8 | (June 1982) |
| | | | | 0— 3.4 | (Jan. 1984) |
| Tanker route | Surface | 17.1± 4.1 | (March 1978) | Surface | 21.7± 1.0(June 1978) |
| | " | 21.5—42.8 | (Dec. 1978) | " | 75.2± 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) | Range | |
| | " | 77—210 | (Oct. 1980) | Arabian Sea | Bay of Bengal |
| | " | 130—267 | (March 1981) | 0—42.8 | 0—28.2 |
| | " | 0— 1.2 | (July 1983) | Average Value | |
| | " | 3.4— 8.5 | (Sept. 1983) | 15.8 | 4.6 |
| | " | 2.1— 5.4 | (Oct. 1983) | | |
| | " | 1.4— 6.1 | (Nov. 1983) | | |
| 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 m^{-2}) | | | | | |
| | | Arabian Sea | | Bay of Bengal | |
| Tanker route | | 0.02— 0.32 | (March 1978) | 0.42— 3.45 | (June 1978) |
| | | 1.26— 3.46 | (June 1978) | 0— 1.6 | (Jan. 1980) |
| | | 0— 0.54 | (Dec. 1978) | 0—69.8 | (Feb. 1980) |
| | | 0.09— 6.0 | (May 1979) | 0— PI | (Jan. 1984) |
| | | 0— 0.53 | (Feb. 1980) | | |
| | | 0.30—112.2 | (March 1981) | | |
| | | 0— 0.06 | (Feb. 1982) | | |
| | | 0— PI | (June 1983) | | |
| | | 0— — | (July 1983) | | |
| | | 0— — | (Sept. 1983) | | |

Table 2. Ranges of Dissolved heavy metal concentrations ($\mu\text{g l}^{-1}$) in the Indian Ocean.

| Source | Cu | Cd | Fe | Mn | Zn | Pb | Ni | Co | Hg(ng l^{-1}) |
|--|-----------|-----------|-----------|-----------|----------|-----------|-----------|--------|--------------------------|
| Topping (1969) | 0.5—49.1 | — | 0.1—61.8 | 0.1—4.6 | 3.9—19.5 | — | — | — | — |
| Chester & Stoner (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. (1978b) | 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 & Moraes (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 and non-essential heavy metals (PPM) wet weight) in zooplankton, crustaceans, bivalve and 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 | 0.02-5.9 | 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 | 4.4 | — | — | — | — | — | <1 | 0.7 | 0.01 | |
| Anchovies | — | — | — | — | — | — | — | — | — | |
| 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 | |

Table 3. (continued)

| Fish | Essential Heavy Metals | | | | | Non Essential Heavy Metals | | | |
|----------------|------------------------|-----------|---------|----------|---------|----------------------------|---------|-----------|------------|
| | Cu | Fe | Mn | Zn | Ni | Co | Pb | Cd | Hg |
| 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.

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 ($\mu\text{g l}^{-1}$) | 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).

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 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 1 per head per 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 river 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 per day) | $53 \times 10^6 \text{ tonnes}$ |
| Fertiliser used per year (@ $30.5 \text{ kg ha}^{-1} \text{ yr}^{-1}$) | $5 \times 10^6 \text{ tonnes}$ |
| Pesticides used per year (@ $336 \text{ g ha}^{-1} \text{ yr}^{-1}$) | 55 000 tonnes |
| Synthetic detergents used per year | 125 000 tonnes |
| Oil transported across the Arabian Sea in 1982 | $579 \times 10^6 \text{ tonnes}$ |
| Oil transported to Western Hemisphere in 1982 | $331 \times 10^6 \text{ tonnes}$ |
| Oil transported to Far East and Japan in 1982 | $248 \times 10^6 \text{ tonnes}$ |
| Tar deposition on beaches along the West Coast of India per year | 750—1000 tonnes |

Table 1A. Relation between the dissolved/dispersed petroleum hydrocarbons in the upper 30 m of the Northern Indian Ocean and oil transport along the tanker routes.

| Year | Transport (mt) | | Concentrations Range (ug/kg) | |
|--|----------------|---------|---------------------------------|---------------|
| | To west | To east | Arabian Sea | Bay of Bengal |
| 1978 | 652 | 323 | 0.9 — 42.5 | 0 — 28.2 |
| 1979 | 659 | 351 | 10.4 — 41.6 | 24.0 — 75.2 |
| 1980 | 561 | 308 | 6.4 — 230.0 | 3.1 — 27.4 |
| 1981 | 455 | 270 | 130.0 — 305.0 | 0 — 4.5 |
| 1982 | 332 | 247 | — | 0 — 2.8 |
| 1983 | 291 | 222 | 0 — 16.2 | — |
| 1984 | 237 | 252 | 1.6 — 22.9 | 0 — 3.4 |
| 1985 | 215 | 232 | 0.7 — 31.0 | 5.2 — 29.5 |
| 1986 | — | — | 1.0 — 23.5 | — |
| Net % decrease from 1978 to 1985 | | | | |
| | 67 | 28 | | |