

Oceanography of the northern Arabian Sea

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Abstract—The euphotic zone of the northern Arabian Sea ranges from 20 to 60 m with an average depth of about 40 m. Surface temperatures range from 22.5 to 28.5°C, increasing from north to south. At 1000 m, the temperature is about 15°C lower than at the surface. Maximum difference in temperature is found during the SW monsoon. Salinity also decreases from north to south. High salinity in the northern region is probably due to the excess of evaporation over precipitation and runoff, and to high salinity water coming from the Persian Gulf. There is little seasonal effect on the salinity, but there are large differences in the dissolved oxygen at the surface during the SW monsoon. There are two oxygen minima, the first between 100 and 400 m and the second between 800 and 1500 m. The formation of the first oxygen minimum is probably due to high organic production in the euphotic zone, sinking of a large amount of organic matter, the lack of horizontal advection due to the land-locked nature of the sea, and the presence of high salinity water in the upper layers. High oxygen at intermediate depths and the second oxygen minimum in the range 800 to 1500 m probably occur as a result of physical processes peculiar to this part of the Arabian Sea. The flow pattern consists of several eddies and meanders. Inorganic phosphorus is high in the surface layer and still higher at greater depths. Nitrate-nitrogen is low at the surface and increases with depth.

Ratios between apparent oxygen utilization (AOU), and changes in carbon, silicon, nitrogen, and phosphorus by atoms were 280:108:40:16:1. Using this relationship it was possible to estimate nitrate reduction at the intermediate depth range and the residence time of water in the oxygen-deficient layer. The rate of primary production in the northern Arabian Sea was 835 mg C m⁻² day⁻¹ or 530 × 10⁶ tonnes of carbon each year. The average chlorophyll in the euphotic zone was also high. About 25% of the total photosynthetic production of the Arabian Sea occurs in the northern part in about 8% of the area. Zooplankton biomass was also several times that in the rest of the Arabian Sea, and was largely confined to the upper 200 m. Benthic biomass, on the other hand, was lower than in the other regions of the Indian Ocean.

INTRODUCTION

ONE of the most important features of the northern Arabian Sea (15 to 26°N, 50 to 74°E) is that its northern boundary is closed by land mass. Barring its southern end, which is open and merges with the rest of the Arabian Sea, it is a semi-enclosed sea. Despite the observations made during the International Indian Ocean Expedition (IIOE), large regions of the northern Arabian Sea, including the Gulf of Oman and Persian Gulf, have remained unknown or poorly known.

Between December 1973 and May 1974 the Indian Naval Ship (INS) *Darshak* undertook five oceanographic cruises, and from February to October 1976 the R.V. *Gaveshani* carried out four cruises in the northern Arabian Sea. The data from these cruises plus data from the IIOE have been used to describe the oceanography of the northern Arabian Sea.

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MATERIALS AND METHODS

This paper is based on 21 cruises covering all months of the year (four cruises of R.V. *Gaveshani* in February, March, October, and November 1976, five cruises of INS *Darshak* in December 1973, January, February, March, April, and May 1974, and 13 cruises of IIOE from 1960 to 1965, which include all months of the year except October), a total of 411 stations (Fig. 1). However, for each variable the number of observations differs because not all the variables were measured by each ship. All the data for a specific variable were plotted on 1° squares and averaged for the whole year to draw isopleths at four different depths. The data were then regrouped according to the season—premonsoon from February to May, SW monsoon from June to September, and NE monsoon from October to January.

Water samples were collected using TPN water samplers (type Hydrobios, Kiel) during *Darshak* cruises and Van Dorn bottles during *Gaveshani* cruises, in addition to metallic Nansen bottles used on all cruises. Temperature was observed with deep-sea reversing thermometers and salinity was determined using an inductive salinometer or an Autosol Model 8400. At 72 stations during *Darshak* cruises, continuous profiles of temperature and salinity against depth were obtained using a Plessey 9060 STD recorder. Subsamples for the various chemical analyses were drawn immediately and analysed onboard according to the details given by SEN GUPTA, FONDEKAR, SANKARANARAYANAN and DE SOUSA (1975) and SANKARANARAYANAN (1978). The procedures for the various other determinations are outlined below.

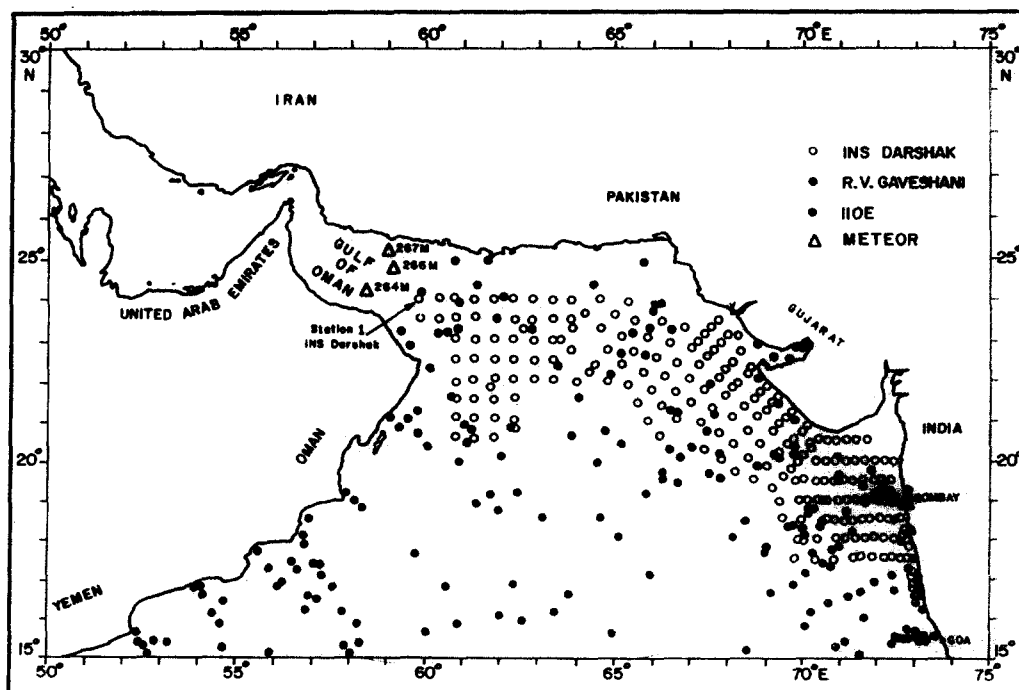


Fig. 1. Position of stations occupied by different ships in the northern Arabian Sea at which data on different aspects of oceanography were collected.

Light

Light transmission was measured using a submarine photometer (Model No. 268, WA 300, G.H. Manufacturing and Instrument Corporation). It consisted of an underwater photocell and a deck photocell, each with 50% sensitivity within the spectral range 4000 to 6400 Å. Light intensity was measured at intervals of 5 m at each station to the depth of 1% of the incident illumination (VARKEY and KESAVADAS, 1976).

Phytoplankton production

A radiocarbon method was used for the determination of primary production. On *Darshak* and *Gaveshani*, samples taken from several light penetration depths within the euphotic zone were incubated for 24 h under simulated *in situ* conditions (RADHAKRISHNA, DEVASSY, BHARGAVA and BHATTATHIRI, 1978). The IIOE data, compiled by BABENERD and KREY (1974), were from the northern Arabian Sea. All the values thus obtained were plotted and averaged for drawing the isopleths. Chlorophyll *a* was determined on *Darshak* using a spectrophotometer and trichromatic equations with no correction for pheopigments. On *Gaveshani* cruises a fluorometer was used for chlorophyll *a* measurements and the values were corrected for pheopigments. The IIOE chlorophyll *a* data were taken from BABENERD and KREY (1974).

Zooplankton biomass

Vertical hauls from 200 m to the surface were made using the Indian Ocean Standard Net (IOSN) to obtain zooplankton samples. In some cruises a Heron-Tranter (HT) square net with a flow meter was used. In nearshore areas, where the depth was less than 200 m, hauls were from the bottom to the surface. Displacement volume of each haul was determined and converted to ml m⁻² by multiplying by the actual depth.

Benthic biomass

Benthic samples were collected using a snapper, a grab, or a dredge. The selection of the sampler was made after determining the depth and the type of sediment. The samples were subsampled, sieved through 0.5-mm stainless steel mesh; the animals obtained by sieving largely included macrobenthos whose biomass was expressed on a dry weight basis. For the collection of meiobenthos, a core tube 10 cm long and 3.4 cm² in cross section was inserted in the collected sample. The top 5 cm of the core was preserved in Rose Bengal and 5% formaldehyde and sieved through 0.062-mm mesh. The animals retained were taken as meiobenthos.

RESULTS AND DISCUSSION

Light

Light penetration was observed at 98 stations, both shallow (coastal) and deep (oceanic). The depth of 1% illumination (euphotic zone) in the northern Arabian Sea is shown in Fig. 2; the depth ranged between 20 and 60 m with an average of about 40 m. It generally increased from nearshore to offshore, but pockets of high and low values were evident in the deep areas. The shallow zone off Oman along 61°E was a distinctive feature. High values of primary production and chlorophyll *a* were also observed in these areas. The average depth of the euphotic zone in the northern Arabian Sea (40 m) is significantly less than that of the

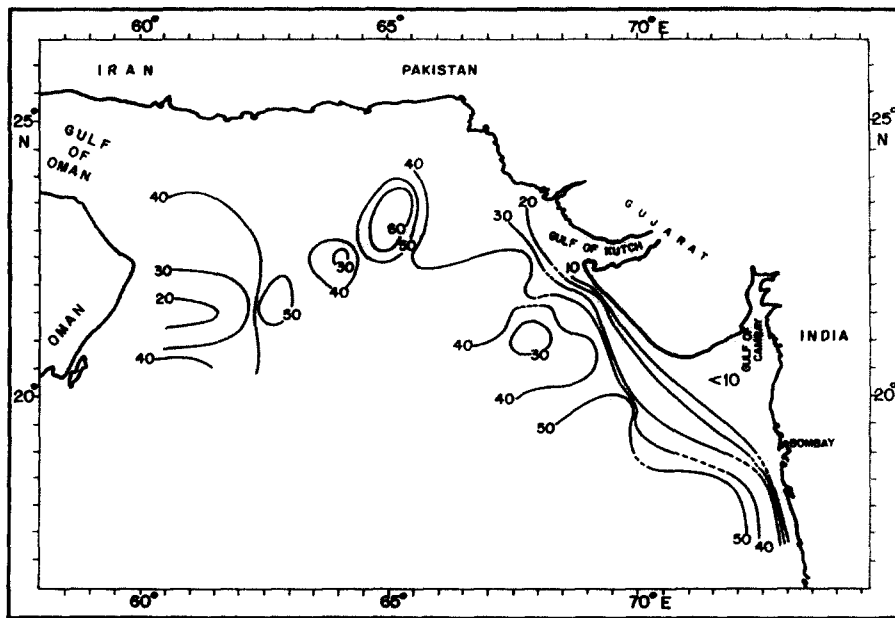


Fig. 2. Depth (m) of 1% illumination (euphotic zone) in the northern Arabian Sea.

southern part of the Arabian Sea, where the average is about 60 m (QASIM, 1977). The shallowness of the photic depth is a characteristic feature of fertile waters.

In the Gulf of Cambay, the euphotic zone was less than 10 m deep; at one station it was about 1 m thick because of large amounts of inert material (suspended silt, sand etc.) in the waters; strong tidal currents in the area stir up bottom material and bring it into suspension. Off Bombay, the 40-m contour of 1% illumination lies about 70 km from the shore whereas it is 270 km from the mouth of the Indus river; the Indus introduces large quantities of suspended (terrigenous) matter. In most of the other areas, the reduction in light penetration seems to be associated with high biological productivity.

Off Bombay, the transparency of offshore waters is largely controlled by suspended organic matter, but in shallow waters the stirring up of bottom sediments influences the transparency. Sewage and industrial waste discharged from Bombay city also influence the light transmission in the Bombay waters. Figure 3 shows the distribution of the mean attenuation (extinction) coefficient of light in the euphotic zone. The attenuation coefficients are high in the coastal regions that correspond to the shallow euphotic zone shown in Fig. 2. These were also high off Oman (Fig. 3). As the depth of the euphotic zone and the attenuation coefficient are directly related, the features in both figures are comparable. The highest attenuation coefficient of 4.6 was found in coastal waters. On the basis of attenuation coefficients, VARKEY and KESAVADAS (1976) divided the northern Indian Ocean into three categories: (1) oceanic ($E_D \leq 0.15$); (2) coastal ($0.15 < E_D < 0.46$); and (3) very turbid ($E_D \geq 0.46$).

Temperature

The temperature regime of the northern Arabian Sea from 0 to 1000 m depth is shown in Fig. 4. The data are largely from 208 *Darshak* observations at the surface, 96 at 100 m, 94 at 500 m, and 90 at 1000 m.

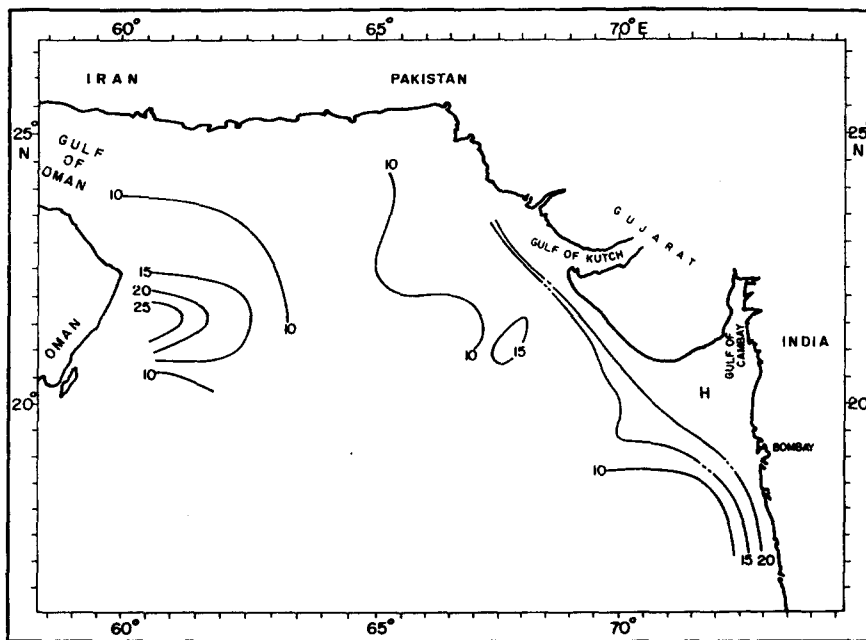


Fig. 3. Attenuation coefficient of the euphotic zone ($E_D \times 10^2$) in the northern Arabian Sea.

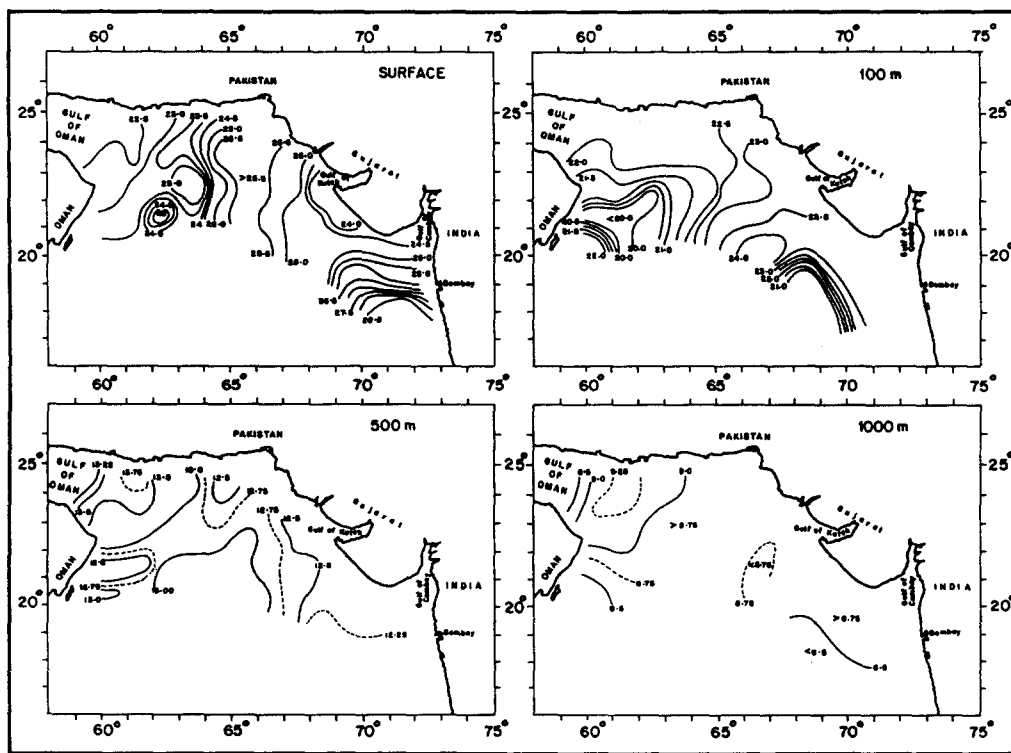


Fig. 4. Distribution of temperature ($^{\circ}\text{C}$) at four different depths of the northern Arabian Sea.

At the surface, the temperature ranged from 22.5 to 28.5°C with a distinct increase from north to south. Deeper (500 and 1000 m), there was a decrease in temperature from north to south. In the inshore areas, the water was isothermal in the upper 30 to 40 m, but in the deeper parts the isothermal layer extended from 75 to 125 m, below which there was a sharp thermocline between 100 and 200 m. At 500 m, the temperature was 12.25 to 13.75°C lower than at the surface. At 1000 m, the temperature varied from 8.5 to 9.25°C. In the southwest, the water at this depth was warmer than in the southeast. The temperature at 1000 m was from 14 to 19°C lower than at the surface.

The general surface warming from north to south and offshore may be because of cooling of the land mass in the northern region and a general flow of cold air from the land causing more cooling of the sea close to the land (SANKARANARAYANAN, 1978).

The seasonal changes in temperature in the northern Arabian Sea are shown in Table 1. During the premonsoon season, the differences are about 7°C, whereas during the SW monsoon surface temperature difference is about 12°C; heating and cooling of the surface water become widespread over the entire region. During the NE monsoon, the temperature difference is only about 7°C. Even at 100 m the seasonal temperature effect is marked and during the SW monsoon the difference in temperature from one region to the other could be of the order of 10°C. In the other two seasons (NE monsoon and premonsoon), there is a difference of about 7°C. At greater depths (500 and 1000 m) the effect of the SW monsoon on temperature is evident as the range in temperature remains large, whereas in the other two seasons it decreases to only about 1°C (Table 1).

Table 1. Seasonal variations in temperature (°C) at four different depths of the northern Arabian Sea

Depths	Season	Minimum	Maximum	Average	sd
Surface	Premonsoon (Feb–May)	22.17	29.31	25.35	2.137
	SW Monsoon (June–Sept)	18.36	30.12	26.18	2.752
	NE Monsoon (Oct–Jan)	22.55	29.03	25.06	1.338
100 m	Premonsoon (Feb–May)	18.92	24.24	22.61	0.950
	SW Monsoon (June–Sept)	16.05	26.49	21.13	2.437
	NE Monsoon (Oct–Jan)	19.26	26.05	20.83	1.807
500 m	Premonsoon (Feb–May)	11.69	14.07	12.88	0.471
	SW Monsoon (June–Sept)	11.20	18.82	12.45	1.051
	NE Monsoon (Oct–Jan)	11.94	13.05	12.57	0.379
1000 m	Premonsoon (Feb–May)	8.39	9.43	8.90	0.247
	SW Monsoon (June–Sept)	8.01	13.58	8.98	0.706
	NE Monsoon (Oct–Jan)	8.25	9.07	8.75	0.232

Salinity

The distribution of salinity (Fig. 5) is largely based on observations during *Darshak* cruises. The surface salinity varied from 35.4 to 36.6×10^{-3} and decreased from north to south. At 100 m there was no significant difference in the range of salinity, but at 500 m the salinity was lower. At 1000 m, the salinity range was only 35.3 to 35.5×10^{-3} , with an average of about 35.4×10^{-3} throughout the region. The low surface salinity off the west coast of India south of 20°N is not due to rainfall or land runoff as no major rivers enter this area and the rainfall in the region is quite low. The low salinity water, largely confined to the top 100 m, may be due to the inflow of water of lower salinity from the south. From the surface to 1000 m, the salinity decreases from north to south and from west to east. The high salinity in the north is due to the inflow of highly saline water from the Persian Gulf. In the northwest Arabian Sea, the annual excess of evaporation over precipitation has been reported to be about 1000 mm by VENKATESWARAN (1956) or 1000 to 1500 mm by WARREN, STOMMEL and SWALLOW (1966). A similar feature may account for the high salinities of the northern Arabian Sea. VARMA, DAS and GOUVEIA (1980) studied the thermohaline structure in the northern Arabian Sea. They found that Persian Gulf water was generally present at about 300 m and that it is not found along the west coast of India.

Seasonal changes in salinities (0 to 1000 m) are shown in Table 2. There is little effect of seasons on the salinity. During the premonsoon season, when the maximum surface salinity was 37.06×10^{-3} , there was a difference of about 2×10^{-3} from minimum to

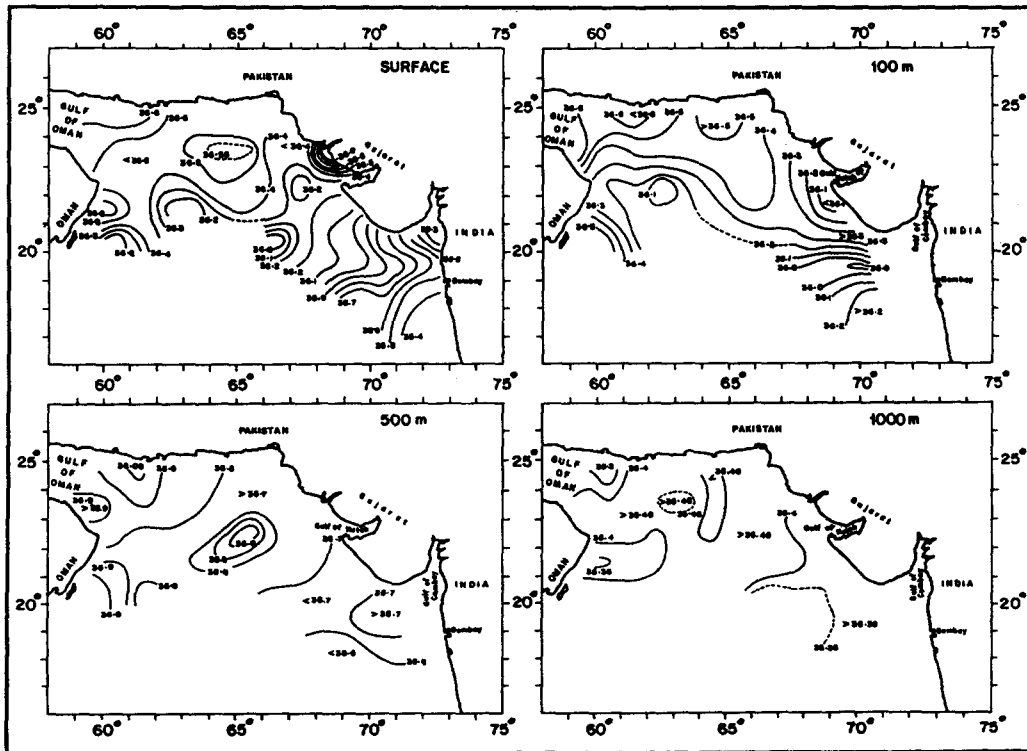


Fig. 5. Distribution of salinity ($\times 10^3$) at four different depths of the northern Arabian Sea.

Table 2. Seasonal variations in salinity ($\times 10^3$) at four different depths of the northern Arabian Sea

Depth	Season	Minimum	Maximum	Average	sd
Surface	Premonsoon (Feb–May)	35.00	37.06	36.13	0.448
	SW Monsoon (June–Sept)	35.04	36.89	36.19	0.369
	NE Monsoon (Oct–Jan)	35.12	36.74	36.00	0.375
100 m	Premonsoon (Feb–May)	36.10	36.68	36.40	0.128
	SW Monsoon (June–Sept)	35.35	36.47	36.00	0.315
	NE Monsoon (Oct–Jan)	35.54	36.53	36.15	0.217
500 m	Premonsoon (Feb–May)	35.54	36.83	35.80	0.157
	SW Monsoon (June–Sept)	35.08	35.89	35.63	0.123
	NE Monsoon (Oct–Jan)	35.65	36.04	35.78	0.120
1000 m	Premonsoon (Feb–May)	35.05	35.63	35.40	0.069
	SW Monsoon (June–Sept)	35.07	35.90	35.41	0.109
	NE Monsoon (Oct–Jan)	35.29	35.52	35.39	0.057

maximum values. In the other seasons (NE and SW monsoon), the changes were small (about 1.5×10^{-3}) at the surface. At greater depths (100, 500, and 1000 m), the seasonal differences are not well marked and are in a range of 0.5 to 1×10^{-3} .

Oxygen

The oxygen concentrations at the surface ranged from 4.2 to 5.2 ml l^{-1} and increased from north to south (Fig. 6). At 100 m they ranged from 0.9 to 4.5 ml l^{-1} , and there was a distinct decrease from the coast offshore. At 500 m, the oxygen was still lower, between 0.2 to 1.6 ml l^{-1} . At 1000 m, it increased from 0.3 to 1 ml l^{-1} with no definite horizontal pattern.

Oxygen values for three seasons at four different depths are given in Table 3. Although the average surface values do not differ widely seasonally, there is a large difference (4.47 ml l^{-1}) during the SW monsoon. At 100 m, the premonsoon average is the highest, but the range is maximum during the SW monsoon and minimum during the NE monsoon. At 500 and 1000 m seasonal differences are not pronounced except that the values are lowest during the SW and NE monsoons (Table 3).

SEN GUPTA *et al.* (1975) reported two oxygen minimum layers, one between 100 and 400 m, another between 800 and 1500 m. The former was probably because of limited mixing, high organic production, and sinking and decomposition of large amounts of organic matter. Also the supply of oxygen from the layer above the first oxygen minimum layer is limited by the thermocline. The deeper minimum is probably because of limited horizontal advection and the oxygen maxima at intermediate depth. According to NEYMAN (1961), the high salinity, high temperature, oxygen-poor waters of the Persian Gulf and Gulf of Aden sink and spread into the subsurface layers. RAO and JAYARAMAN (1970) suggested that the upper

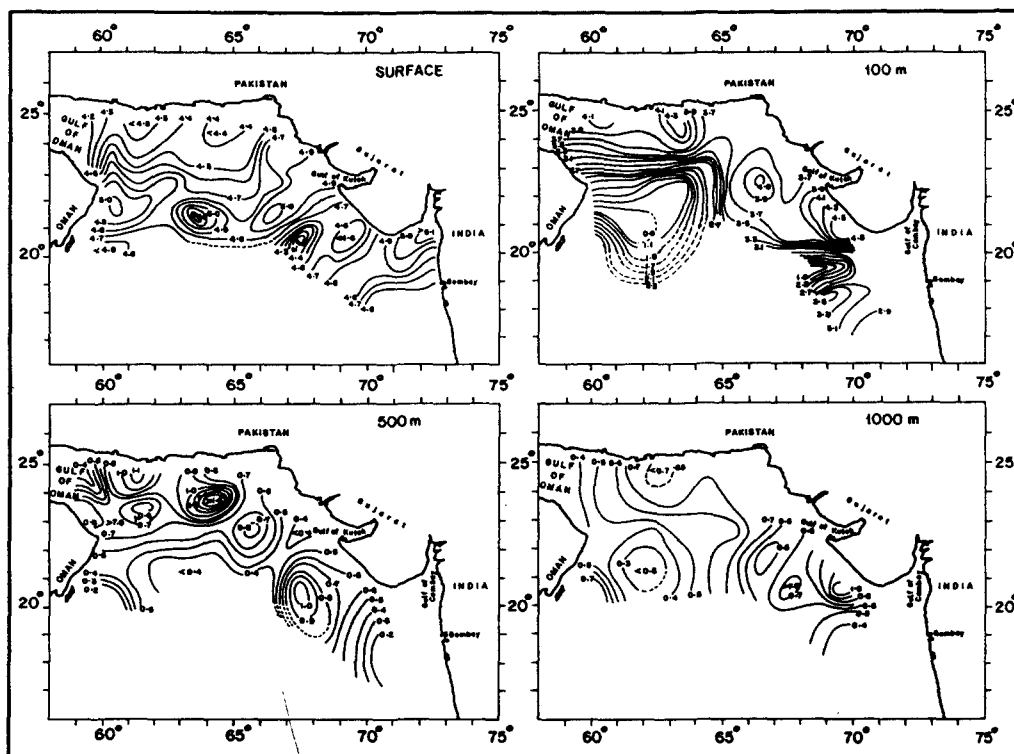


Fig. 6. Distribution of dissolved oxygen concentration (ml l^{-1}) at four different depths of the northern Arabian Sea.

oxygen minimum is because of near-stagnant conditions in the northern and central parts of the Arabian Sea. IVANENKOV and ROZANOV (1961) reported the occurrence of hydrogen sulphide in the northern Arabian Sea; this was not confirmed during the *Darshak* or *Gaveshani* cruises, although oxygen concentrations were always low. According to WYRTKI (1973) the layer is due to isolation and stagnation of the intermediate water, limited horizontal advection, and high primary productivity.

The maximum sill depth in Hormuz Strait is about 100 m (SEIBOLD and ULRICH, 1970). Although towards the southwestern end of the strait the depth at some places is about 200 m, Persian Gulf water does not seem to flow below 100 m, because the maximum depth 72 km south of the Hormuz Strait into the Gulf of Oman is only about 100 m. The Persian Gulf is an area of high evaporation with highly saline water ($\sim 40 \times 10^{-3}$). This water first sinks in the central portion of the Persian Gulf and then flows over the sill into Hormuz Strait to the Gulf of Oman.

Vertical profiles of oxygen at the three southernmost *Meteor* stations and one northern station of *Darshak* (Sta. 1) have been plotted in Fig. 7 and located in Fig. 1.

Although the depth decreases from Sta. 264 to 267 (SW to NE), the upper minimum remains between 100 and 150 m, apparently the depth of the Persian Gulf inflow. In the central Gulf of Oman (Sta. 1 INS *Darshak*) a deeper minimum is at about 500 m and extends to more than 1000 m. *Meteor* Stas 264 and 266 show a similar feature except that at the

Table 3. Seasonal variations in oxygen (ml l^{-1}) at four different depths of the northern Arabian Sea

Depth	Season	Minimum	Maximum	Average	sd
Surface	Premonsoon (Feb–May)	3.70	5.46	4.62	0.291
	SW Monsoon (June–Sept)	1.94	6.41	4.49	0.641
	NE Monsoon (Oct–Jan)	4.37	5.36	4.84	0.235
100 m	Premonsoon (Feb–May)	0.61	4.82	3.41	0.901
	SW Monsoon (June–Sept)	0.16	5.07	1.74	1.210
	NE Monsoon (Oct–Jan)	0.33	3.65	1.22	0.826
500 m	Premonsoon (Feb–May)	0.12	1.26	0.65	0.293
	SW Monsoon (June–Sept)	0.07	0.95	0.30	0.410
	NE Monsoon (Oct–Jan)	0.09	1.11	0.50	0.271
1000 m	Premonsoon (Feb–May)	0.20	1.13	0.60	0.191
	SW Monsoon (June–Sept)	0.11	0.79	0.39	0.169
	NE Monsoon (Oct–Jan)	0.07	0.73	0.35	0.181

shallow Sta. 264 the oxygen increases below 500 m (Fig. 7). At *Meteor* Sta. 267, the shallowest of the four, the second oxygen minimum appears at about 300 m and at greater depths oxygen increases. The minimum at depths of 100 to 150 m is at sigma- t values of 26.8 to 27.1.

The waters at greater depths appear to have a sluggish circulation, and the oxygen-depleted water has a long residence time in the Gulf of Oman. Earlier studies indicated that water flowing from the Persian Gulf into the Gulf of Oman at about 150 m forms 70 to 80% of the water mass at that depth (DÜING and SCHWILL, 1967): The northernmost *Darshak* station (see Fig. 1) is about 225 km southeast of *Meteor* Sta. 266. The oxygen minimum at 150 m evidently arises because of the influx of oxygen-poor Persian Gulf water into the northern Arabian Sea. The minimum at 500 to 800 m is also probably due to the flow from Sta. 266 to Sta. 1 (see Fig. 1). However, the other northern Indian Ocean water masses may enter at depths of 500 to 800 m and affect the oxygen content. SEN GUPTA, SANKARANARAYANAN, DE SOUSA and FONDEKAR (1976) observed the two oxygen minima as far south as 18°N, and later observations showed that the two minima could be traced to 11°N (SEN GUPTA *et al.*, 1979). The minimum is not prominent near the west coast of India, where one large, thick minimum layer is observed (SEN GUPTA, BRAGANCA, NORONHA and SINGBAL, 1980).

In summary, the upper oxygen minimum is a result of biodegradation of organic matter in oxygen-poor water from the Persian Gulf, while the deeper one probably originates in the deep waters of the Gulf of Oman and mixes with similar water masses coming from the southern regions of the Arabian Sea.

Circulation

Little is available on the flow patterns in the northern Arabian Sea, particularly north of 20°N. ROCHFORD (1964) discussed the flow of various water masses. RAMAM, KURUP and

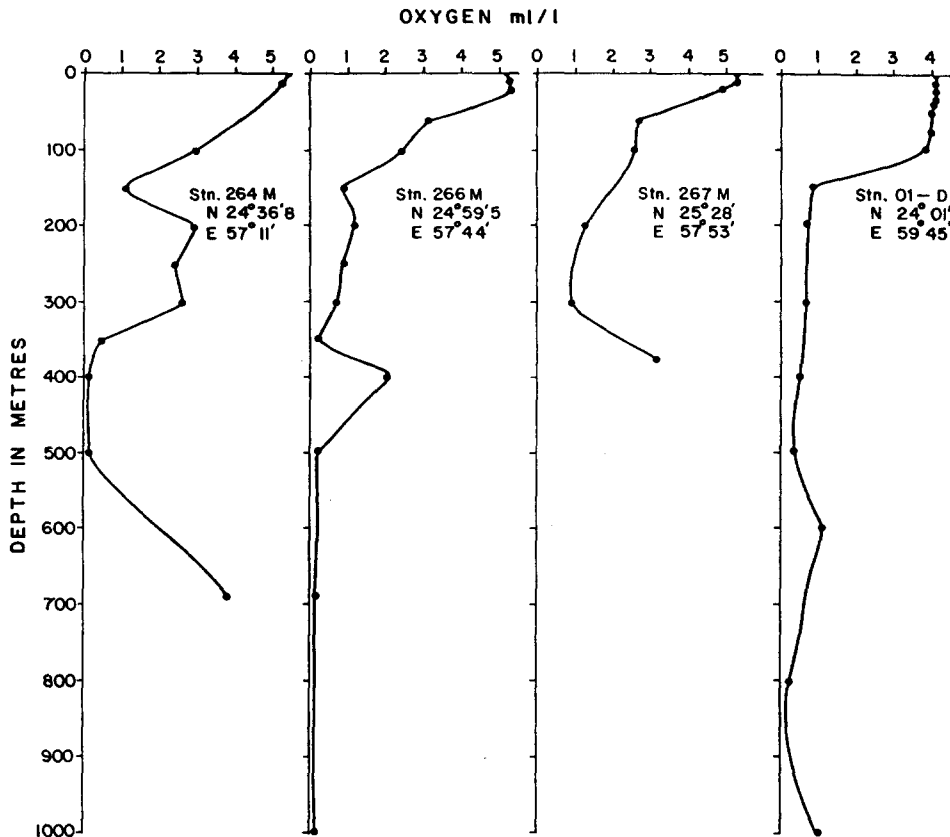


Fig. 7. Vertical profiles of dissolved oxygen at four stations in the Gulf of Oman. Stations 264 M, 266 M, and 267 M are *Meteor* stations and Sta. 01-D is the first station of INS *Darshak*.

MURTHY (1968) identified four different water masses in the Arabian Sea: (1) Persian Gulf water; (2) Gulf of Oman water; (3) Indus water; and (4) Red Sea water. Other studies are those of WOOSTER, SCHAFFER and ROBINSON (1967), WYRTKI (1973), and SASTRY and DE SOUZA (1970). More recently DAS, GOUVEIA and VARMA (1980) studied the distributions of salinity, temperature, and depth at 72 stations using an STD profiler. The data were used to deduce the geostrophic flow on isanosteric surfaces from the gradient of acceleration potential. The geostrophic flow was expressed by MONTGOMERY and STROUP (1962) as

$$\phi_a + P\delta = P_0\delta_0 + \int_{\delta_0}^{\delta} P d\delta,$$

where $\phi_a + P\delta$ is the acceleration potential, P is the pressure, δ is the steric anomaly, and P_0 and δ_0 are the pressure and steric anomaly at the reference pressure.

Circulation on 260, 200, 160, and 120-cg t⁻¹ surfaces are presented in Fig. 8. The circulation pattern consists of several eddies and meanders, with a pronounced anticyclonic eddy around 24°N, 64°E. In general, the eddies appear to have appreciable deep vertical extension. The eddy circulation is attributed to the influence of bottom topography, which is marked by depressions and rises (DAS *et al.*, 1980). There are no earlier detailed studies on the circulation

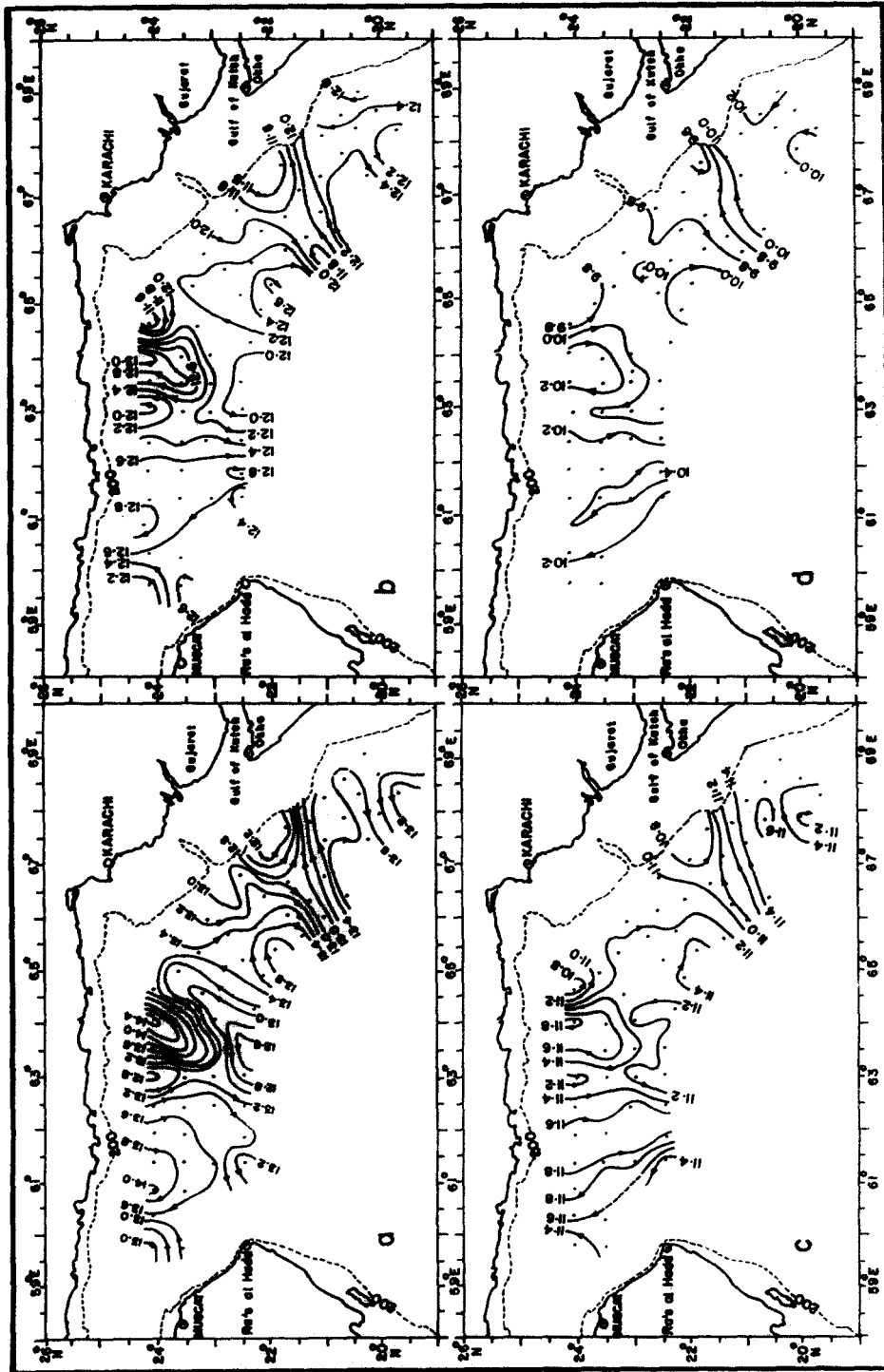


Fig. 8. Distribution of acceleration potential on (a) 260, (b) 200, (c) 160, and (d) 120 cl^{-1} .

in the northern Arabian Sea, but the surface currents as deduced from ship's drift data (KNMI, 1952) show flows of opposing directions, evidence of the presence of eddies. Also, the dynamic topography during March and April given by WYRTKI (1971) indicates meandering flow.

The salinity distribution at different depths indicates (see Fig. 5) that the upper 500 m is characterized by both salinity maxima and minima; the maximum salinity is generally at around 300 m. The water at this depth has been identified by VARMA *et al.* (1980) as Persian Gulf water. The distribution of the core values of such water indicates that it might spread as a tongue southward in the region west of 63°E but not east of 63°E. Apparently the chief flow of Persian Gulf water is not along the west coast of India (VARMA *et al.*, 1980); this is not in agreement with WYRTKI (1971), but it agrees with ROCHFORD (1964), who showed that the main flow of Persian Gulf water is southward through the western part of the Arabian Sea. However, WYRTKI (1971) also suggested a flow of Persian Gulf water to the Somali Basin during the NE monsoon.

Nutrients

Inorganic phosphorus. Surface phosphate concentrations at a few stations were relatively high, between 0.5 and 1.75 $\mu\text{g-at. l}^{-1}$ (Fig. 9). They were higher in the northern and southwestern parts and decreased to 1.0 to 0.5 $\mu\text{g-at. l}^{-1}$ in the southeast. At 100 m, the values were generally between 1.0 and 3.5 $\mu\text{g-at. l}^{-1}$. The highest were in the central part. At

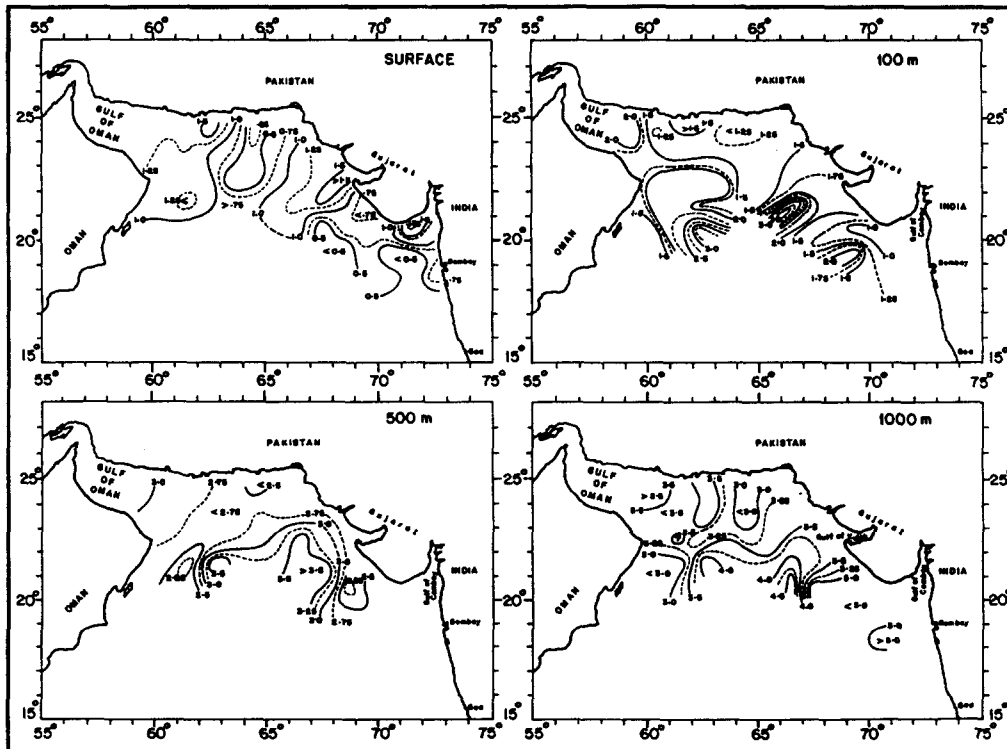


Fig. 9. Distribution of phosphate-phosphorus ($\mu\text{g-at. l}^{-1}$) at four different depths of the northern Arabian Sea.

500 m the values increased from north to south. At 1000 m, values ranged between 3.0 and 4.5 $\mu\text{g-at. l}^{-1}$, with the highest again in the central region (Fig. 9).

Generally concentrations were specially high north of 20°N. High concentrations of phosphate in the upper layers of water are generally attributed to fresh water influx or to upwelling. In the northern Arabian Sea there is little river discharge (*ca.* 208 $\text{km}^3 \text{y}^{-1}$, RAO, 1975), and most of the phosphate appears to come from subsurface layers by thermohaline convection. Upward slopes of most of the hydrographic parameters (VARMA *et al.*, 1980) indicate upwelling from February to April. Below the thermocline (75 m) the phosphate content increases sharply at 100 m (Fig. 9) and then continues to increase monotonically with depth.

Although the average surface phosphate concentrations are the lowest in all seasons, during the SW and NE monsoons the range in values is large (Table 4). At 100 m, the average value and range are maximum during the NE monsoon (Table 4). Unfortunately, few data are available at 500 and 1000 m for the SW monsoon. However, the range and average values (Table 4) suggest that seasonal differences in the deeper layers are small.

Nitrate-nitrogen. At the surface, nitrate concentrations decrease from north to south and from west to east (Fig. 10), with the lowest concentrations off the west coast of India. At 100 m, except for some northern and western areas, the concentrations remained low. At 500 m, average values increased and ranged between 5 and 15 $\mu\text{g-at. l}^{-1}$. At 1000 m, there was no further increase in concentration except in some areas of the north (Fig. 10).

At the surface and at 100 m, the maximum average value and maximum range in nitrate-nitrogen are during the SW monsoon (Table 5). The range in surface values was 0.01 to 25.50 $\mu\text{g-at. l}^{-1}$ during the SW monsoon; at 100 m, the average was 22.25 $\mu\text{g-at. l}^{-1}$ (Table 5).

Table 4. Seasonal changes in phosphate-phosphorus ($\mu\text{g-at. l}^{-1}$) from four different depths of the northern Arabian Sea

Depth	Season	Minimum	Maximum	Average	sd
Surface	Premonsoon (Feb–May)	0.22	2.43	1.00	0.491
	SW Monsoon (June–Sept)	0.11	2.16	0.68	0.499
	NE Monsoon (Oct–Jan)	0.00	2.04	0.80	0.520
	Premonsoon (Feb–May)	0.77	2.43	1.55	0.418
100 m	SW Monsoon (June–Sept)	1.36	2.24	1.89	0.330
	NE Monsoon (Oct–Jan)	1.23	3.40	2.12	0.422
	Premonsoon (Feb–May)	2.03	4.35	3.03	0.523
	SW Monsoon (June–Sept)	Not enough data		–	–
500 m	NE Monsoon (Oct–Jan)	2.08	4.50	2.73	0.502
	Premonsoon (Feb–May)	2.71	4.61	3.39	0.471
	SW Monsoon (June–Sept)	Not enough data		–	–
	NE Monsoon (Oct–Jan)	2.45	4.50	3.07	0.488

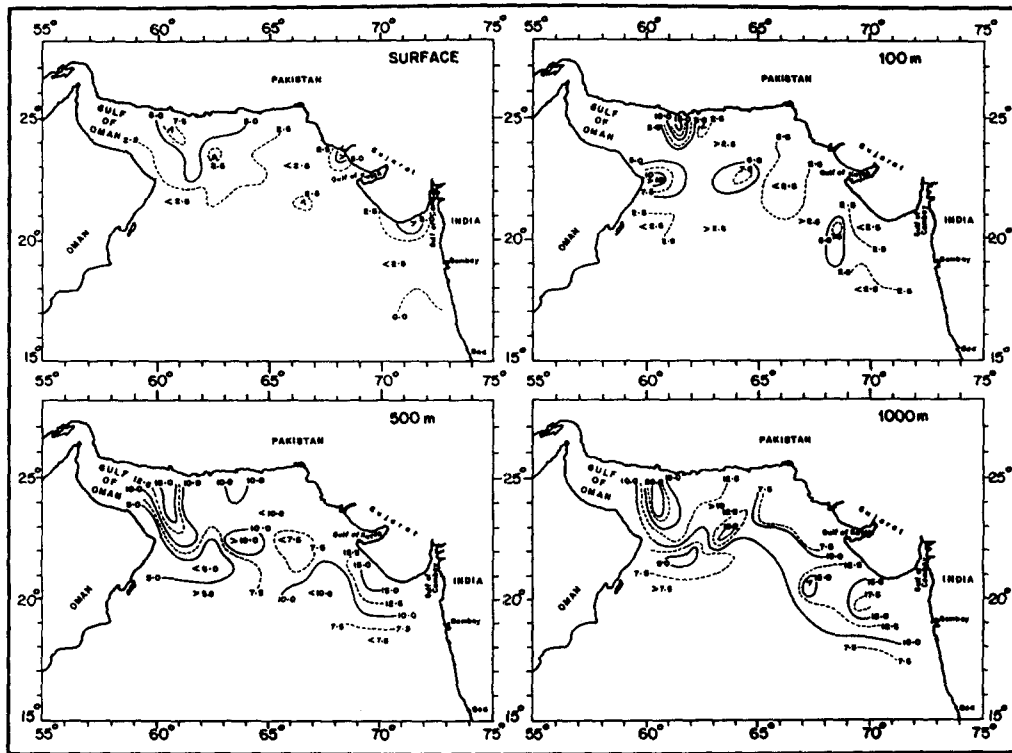


Fig. 10. Distribution of nitrate-nitrogen ($\mu\text{g-at. l}^{-1}$) at four different depths of the northern Arabian Sea.

Table 5. Seasonal variations in nitrate-nitrogen ($\mu\text{g-at. l}^{-1}$) from four different depths of the northern Arabian Sea

Depth	Season	Minimum	Maximum	Average	sd
Surface	Premonsoon (Feb–May)	0.00	8.71	2.05	2.200
	SW Monsoon (June–Sept)	0.01	25.50	6.72	6.895
	NE Monsoon (Oct–Jan)	0.00	12.14	1.75	2.150
	Premonsoon (Feb–May)	0.66	15.11	3.82	2.671
100 m	SW Monsoon (June–Sept)	14.4*	28.5*	22.25	4.540
	NE Monsoon (Oct–Jan)	1.52	12.46	3.96	2.950
	Premonsoon (Feb–May)	2.88	20.75	9.03	3.137
	SW Monsoon (June–Sept)	Not enough data	–	–	–
500 m	NE Monsoon (Oct–Jan)	2.30	28.00	5.45	5.538
	Premonsoon (Feb–May)	3.96	24.66	11.95	4.727
	SW Monsoon (June–Sept)	Not enough data	–	–	–
	NE Monsoon (Oct–Jan)	2.90	29.58	7.38	5.678

* Based on 6 observations.

There are too few data for the SW monsoon at 500 and 1000 m to estimate the range during this season. During the premonsoon and NE monsoon, the range in deeper layers is fairly large.

Nutrient-oxygen relationships

The distribution of nutrients in the upper 100 m generally differed in the Gulf of Oman and in the rest of the northern Arabian Sea. Premonsoon data from the Gulf of Oman were taken from *Meteor* (1964 to 1965) and by *Darshak* (but in different years).

The water in the upper 100 m of the Gulf of Oman is largely water from the Persian Gulf, while in the northern Arabian Sea the water is largely comprised of surface waters from the India-Pakistan coastal regions. In both the Gulf of Oman and the northern Arabian Sea the concentrations of phosphate-phosphorus increase with depth and become about the same at depth.

Silicates observed during the *Meteor* expedition were lower in the Gulf of Oman than in corresponding depths in the northern Arabian Sea.

Using *Meteor* data (DIETRICH, DÜING, GRASSHOFF and KOSKE, 1966) and data from the Indo-Soviet Monsoon Experiment (ISMEX 1973), SEN GUPTA, RAJAGOPAL and QASIM (1976) derived the following relationship for the Arabian Sea:

$$\text{AOU} = 32 + \text{Si}^2 / (0.12065 + 0.01025 \text{Si} + 0.00197 \text{Si}^2). \quad (1)$$

The relationship was applied to the silicate values from the Gulf of Oman given by BRETTSCHEIDER, GRASSHOFF, KOSKE and TREPKA (1970) (Table 6).

To calculate the values given in Table 6, the silicate concentrations were grouped first into 5- $\mu\text{g-at. l}^{-1}$ intervals up to 10 $\mu\text{g-at. l}^{-1}$ and then into 10- $\mu\text{g-at. l}^{-1}$ intervals. The corresponding values of apparent oxygen utilization (AOU) were pooled accordingly (Table 6).

The AOU values at zero silicate were about 32 $\mu\text{g-at. l}^{-1}$ for the SW monsoon period (SEN GUPTA *et al.*, 1976). For the Gulf of Oman, Table 6 gives a negative value for AOU at zero silicate, i.e., the surface waters of the Gulf of Oman are supersaturated with oxygen and simultaneously poor in silicate. A similar trend is evident in the table, although the depths corresponding to some values were greater than 1000 m. This is evidently the effect of nutrient-poor water from the Persian Gulf. Nitrate-nitrogen concentrations (Fig. 10) were generally lower than at corresponding depths in other oceans. This probably indicates nitrate-nitrogen loss by nitrate reduction and denitrification at intermediate depths.

SEN GUPTA *et al.* (1976) showed that the ratios between oxygen consumption and phosphate regeneration and between regenerated nitrates and phosphates differ in the water

Table 6. Mean silicate values at observed and calculated apparent oxygen utilization (AOU) (units are in $\mu\text{g-at. l}^{-1}$)

Range	Si Mean	AOU		AOU	
		Observed	Calculated	Calculated	Observed
0	0	-29	-	-	-
1-5	2	14	59	+45	
6-10	8	160	227	+67	
11-20	15	301	345	+44	
21-30	26	402	425	+23	
31-40	36	463	458	-5	
41-50	47	527	478	-49	

masses above and below 150 m. The upper layers had an excess of phosphate but were deficient in nitrate, presumably due to intense photosynthetic productivity in the upper layers as will be shown later. However, below 150 m presumably the only process is the oxidation of organic matter. SEN GUPTA *et al.* (1976) calculated the linear least-square regression among oxygen consumption and the regeneration of nitrate and phosphate

$$\Delta C : \Delta N : \Delta P = 105 : 15 : 1 \text{ by atoms.} \quad (2)$$

The ratio of nitrate to phosphate in the phytoplankton from the region was estimated as 15.4:1 by atoms. This agrees well with the suggestion that the ratios of the change in nutrients in the water should be similar to the ratios in phytoplankton (REDFIELD, 1934).

Using the *Meteor* 1965 data and ISMEX 1973 data, SEN GUPTA *et al.* (1976) arrived at the following atomic relations for the northwestern Indian Ocean

$$\Delta \text{AOU} : \Delta C : \Delta \text{Si} : \Delta N : \Delta P = 280 : 108 : 40 : 16 : 1. \quad (3)$$

Nitrate deficit

It has been shown that at intermediate depths in the northern Arabian Sea nitrate is reduced and this process may give rise to free nitrogen (SEN GUPTA *et al.*, 1976; DEUSER, ROSS and MLODZINSKA, 1978; NAQVI, NORONHA and REDDY, 1982). Presumably the intensity of denitrification decreases southwards, consistent with increases in oxygen concentration and decreases in the thickness of the oxygen minimum layer (SEN GUPTA *et al.*, 1976; NAQVI *et al.*, 1982). DEUSER *et al.* (1978) reported that denitrification in the Arabian Sea extends up to 14°N, whereas SEN GUPTA *et al.* (1976) placed the southern limit of denitrification at 5°N latitude. NAQVI *et al.* (1982) evaluated the two methods of calculating the original nitrate concentration required for the estimation of nitrate deficits and concluded that denitrification extends up to 11°N.

The quantity of nitrate reduction can be estimated from the equation by CLINE and RICHARDS (1972)

$$\delta N = (\text{NO}_3)_{\text{exp}} - (\text{NO}_3)_{\text{obs}} - (\text{NO}_2)_{\text{obs}} \quad (4)$$

exp = expected; obs = observed, where

$$(\text{NO}_3)_{\text{exp}} = (\text{NO}_3)_{\text{ox}} \pm (\text{NO}_3)_{\text{r}} \quad (5)$$

ox = oxidative; r = reserved. Ammonia-nitrogen was not included in the mass balance because of its low concentration (average 0.94 $\mu\text{g-at. l}^{-1}$).

The oxidative fractions of phosphate-phosphorus and nitrate-nitrogen were calculated from equation (3).

$$P_{\text{ox}} = \text{AOU}/280 \quad \text{and} \quad N_{\text{ox}} = \text{AOU}/17.5.$$

The reserved fractions are given by the following equations:

$$P_{\text{r}} = (\text{PO}_4)_{\text{obs}} - P_{\text{ox}} \quad (6)$$

and

$$N_{\text{r}} = (\text{NO}_3)_{\text{obs}} - (\text{NO}_3)_{\text{ox}}. \quad (7)$$

From all the determinations of PO_4 and NO_3 by least-squares regression we get

$$N_r = 12.2 P_r - 1.7. \quad (8)$$

Equation (8) for the northern Arabian Sea is the same as that for the northwestern Indian Ocean (SEN GUPTA *et al.*, 1976). The slope is similar to the 12.5 value obtained by FIADEIRO and STRICKLAND (1968) for the waters off Peru and 13.1 deduced by CLINE and RICHARDS (1972) for the eastern tropical North Pacific.

By combining equations (4), (5), and (8), nitrate deficits for different depths of the northern Arabian Sea can be calculated. The depthwise averages have been used at different stations to reconstruct a nitrate anomaly curve (Fig. 11), which indicates that the depth range of nitrate reduction is approximately 70 to 1750 m. It also indicates that the intensity of nitrate reduction increases in the upper layers of water, reaches its maximum at about 300 m, and decreases thereafter. The total reduced nitrogen can be calculated as about 200 g m^{-2} . An earlier study showed that the total reduced nitrogen at 15°N latitude in the Arabian Sea is about 70 g m^{-2} and occurs between 75 and 1200 m (SEN GUPTA *et al.*, 1980). The corresponding average value for the region between 12 and 15°N is about 45 g m^{-2} (NAQVI *et al.*, 1982). It can be concluded that the intensity and depth range where nitrate is reduced in the Arabian Sea decrease from north to south.

The average value of reduced nitrogen in the northern Arabian Sea is $10.15 \mu\text{g-at. l}^{-1}$. This would give rise to $1.81 \mu\text{g-at. l}^{-1}$ ammonia (RICHARDS, 1965; CLINE and RICHARDS, 1972). The average concentration of ammonia in the region is $0.94 \mu\text{g-at. l}^{-1}$, suggesting that during nitrate reduction, about half of the reduced nitrogen may end up as gaseous nitrogen while the other half may be present as ammonia.

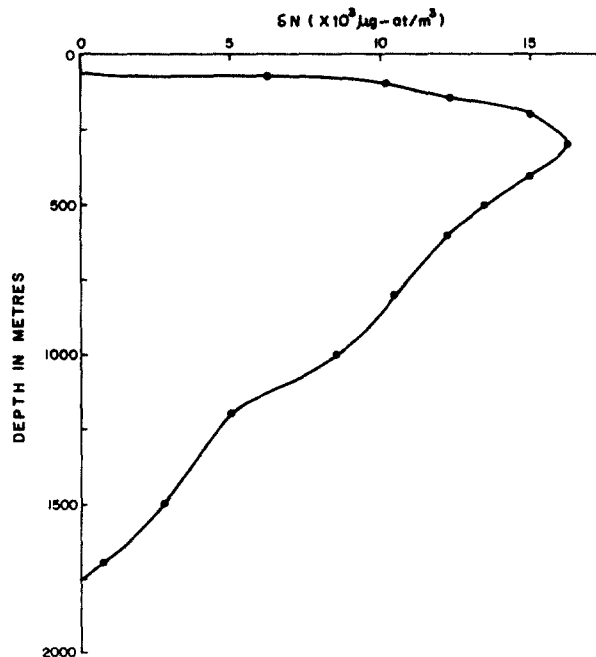


Fig. 11. Calculated nitrogen anomaly (nitrate deficit) in the northern Arabian Sea.

The average concentration of nitrate-nitrogen at the depths of nitrate reduction is $22.40 \mu\text{g-at. l}^{-1}$. The reduced nitrogen has the average value of $10.15 \mu\text{g-at. l}^{-1}$. From the two values, it appears that about 31% of the available nitrate is lost by nitrate reduction. Calculations for the process at different regions of the Arabian Sea gave 34 to 45% (SEN GUPTA *et al.*, 1979, 1980). Thus, about one-third of the available nitrate-nitrogen at intermediate depths is probably lost by nitrate reduction. A high concentration of nitrate is always present at intermediate depths and is probably associated with more nitrifying bacteria than denitrifiers. The small amounts of residual free oxygen at these depths probably gives rise to the oxidation of organic matter.

Nitrate reduction at intermediate depths generally occurs either in areas with high photosynthetic productivity or in the eastern boundary currents that are either closed or have limited openings towards their northern end. Perhaps for this reason, the process has been reported from the Pacific and the Indian oceans but not from the Atlantic, which is well ventilated on its northern side.

The area of the northern Arabian Sea, up to 15°N , is about $1.70 \times 10^6 \text{ km}^2$. The volume between 70 and 1750 m up to 15°N is about $2.856 \times 10^6 \text{ km}^3$. For calculating the volume, the floor dip below 70 m, which is quite steep and so would influence the calculation little, has been excluded. With an average value of $10.15 \mu\text{g-at. l}^{-1}$, it appears that at any time about 406×10^6 tonnes of 'denitrified' nitrogen will be present in these depths.

As will be shown later, the average photosynthetic production rate in the northern Arabian Sea is $835 \text{ mg C m}^{-2} \text{ day}^{-1}$. This would result in 518×10^6 tonnes of carbon per year. It has been observed that about 10% of the photosynthetic production reaches below the euphotic zone (DEUSER, 1971) and about 1% of the total production should give rise to denitrified nitrogen (DEUSER *et al.*, 1978). This value for the production of 'denitrified' nitrogen implies a period of about 77 years to produce 406×10^6 tonnes of denitrified nitrogen. The period was calculated to be 43 years in the depth range 75 to 1200 m by SEN GUPTA *et al.* (1980). If we assume that the depth range of 'denitrified' nitrogen in the northern Arabian Sea is 75 to 1200 m, the required period would be 51 years. This would also mean an average residence time in the layer between 75 to 1200 m to be from 43 to 51 years. Using a rate of outflow from the Persian Gulf of the order of $3 \times 10^3 \text{ km}^3 \text{ y}^{-1}$, HARTMANN, LANGE, SEIBOLD and WALGER (1971) calculated the residence time of Persian Gulf water in the Arabian Sea as 30 years. DEUSER *et al.* (1978) estimated a mean residence time varying from 3 to 30 years for the water mass in the Arabian Sea where denitrification occurs. Considering the limitations inherent in such calculations, the residence time of 43 to 51 years for the oxygen-deficient water appears to be reasonable.

Phytoplankton production

Surface and total water-column production rates for each degree square were grouped, averaged, and plotted in different ranges (Figs 12 and 13). In all, 166 observations were used for calculating the surface production and 118 for column production of the euphotic zone.

Surface production (Fig. 12, Table 7) ranged from 0.2 to $280.7 \text{ mg C m}^{-3} \text{ day}^{-1}$ (average $18.86 \text{ mg C m}^{-3} \text{ day}^{-1}$). Productivity is high in the regions off Bombay, Kutch and Saurashtra, off Pakistan, southern parts of the Gulf of Oman, and off Oman and Yemen. The average production in coastal areas was $37.4 \text{ mg C m}^{-3} \text{ day}^{-1}$ and in the offshore area it was $10.5 \text{ mg C m}^{-3} \text{ day}^{-1}$. The total surface production (within 1-m depth) in the northern Arabian Sea, an area of $1.75 \times 10^6 \text{ km}^2$, is 12.46×10^6 tonnes carbon y^{-1} , an average rate of 7.15 tonnes carbon $\text{km}^{-2} \text{ y}^{-1}$. In the coastal waters (the area within 2° square = $0.56 \times 10^6 \text{ km}^2$)

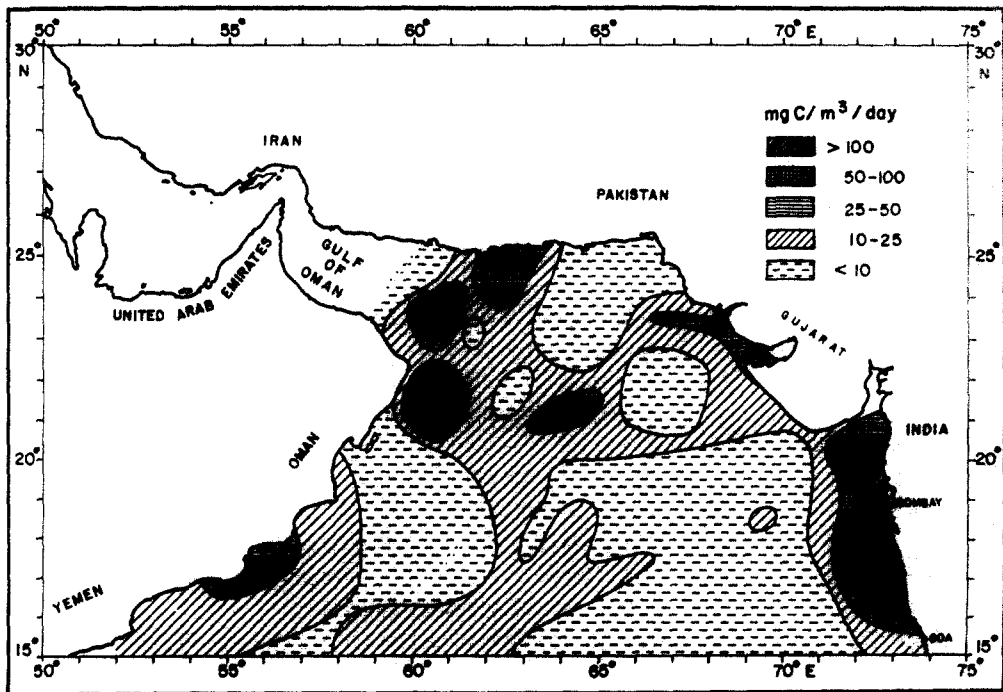


Fig. 12. Rates of primary production (^{14}C uptake) at the surface of the northern Arabian Sea.

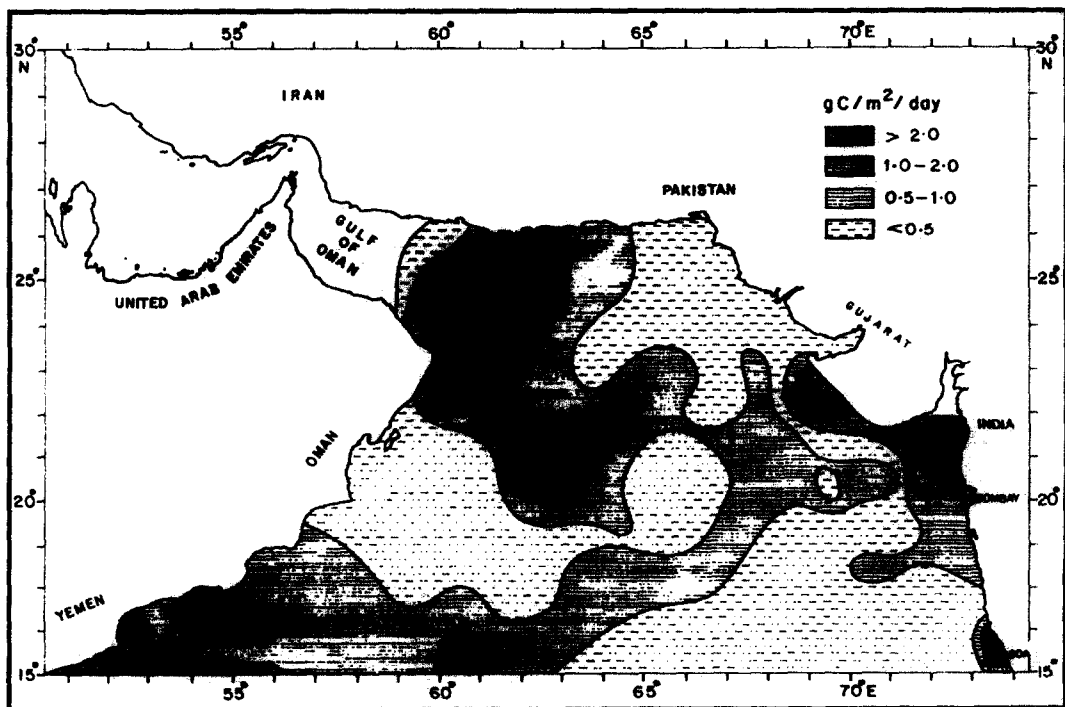


Fig. 13. Rates of primary production (^{14}C uptake) in the euphotic zone of the northern Arabian Sea.

Table 7. Phytoplankton production (primary production and chlorophyll a) in the northern Arabian Sea. Relative production in coastal and offshore waters of the northern Arabian Sea is also given

	Northern Arabian Sea	Coastal waters	Offshore waters
Approximate area (km ²)	1.7×10^6	0.56×10^6	1.18×10^6
Average primary production (surface) (mg C m ⁻³ day ⁻¹)	19.60	37.45	10.51
Total primary production (surface) (tonnes y ⁻¹)	12.45×10^6	7.65×10^6	4.53×10^6
Average primary production (column) (mg C m ⁻² day ⁻¹)	835.0	1329	626
Total primary production (column) (tonnes y ⁻¹)	518×10^6	272×10^6	270×10^6
Average chlorophyll a (surface) (mg m ⁻³)	0.47	0.80	0.26
Average chlorophyll a (0–50 m) (mg m ⁻²)	17.35	26.76	11.32
Total instantaneous chlorophyll a (column) (tonnes y ⁻¹)	30×10^3	15×10^3	13×10^3

the surface production is approximately 7.65×10^6 tonnes carbon y⁻¹ or 13.66 tonnes carbon km⁻² y⁻¹, and in the offshore waters (area = 1.18×10^6 km²) it is 4.53×10^6 tonnes carbon y⁻¹ or 3.84 tonnes carbon km⁻² y⁻¹. In the entire Arabian Sea, the surface production has been estimated to be 24.6×10^6 tonnes carbon y⁻¹ or 3.9 tonnes carbon km⁻² y⁻¹ (QASIM, 1977). This would mean that the northern Arabian Sea gives rise to about 50% of the total surface production of the entire Arabian Sea. Of this, 50% is produced in the coastal water, or about 31% of the total production of the entire Arabian Sea.

Column production (integrated phytoplankton production for the photic zone) ranges from 13.0 to 6010 mg C m⁻² day⁻¹, with an average value of 835 mg C m⁻² day⁻¹ (Fig. 13).

The fertile areas are coastal waters where production was from 42.0 to 6010 mg C m⁻² day⁻¹ (average 1329 mg C m⁻² day⁻¹). In offshore areas, the range is 17.0 to 2180 (average 626 mg C m⁻² day⁻¹). For the entire northern Arabian Sea the total production would be 518×10^6 tonnes of carbon y⁻¹. In the coastal water the column production is about 270×10^6 tonnes of carbon y⁻¹; the coastal waters appear to sustain more than 50% of the total production of the northern Arabian Sea. RADHAKRISHNA *et al.* (1978) reported lower average values of primary production. Their results were based on 19 shelf and 37 offshore stations, but they also concluded that the shelf waters are very fertile.

Seasonal changes in phytoplankton production are given in Table 8. During the SW monsoon it remains low at the surface but it increases during the premonsoon and NE monsoon.

Column production reaches maximum range and average values during the SW monsoon, suggesting that during the SW monsoon most of the primary production occurs below the surface. During the NE monsoon the average is higher than during the premonsoon (Table 8).

The northern Arabian Sea is approximately 25% of the total area of the Arabian Sea, but it supports nearly 50% of the total primary production, and the coastal area of the northern Arabian Sea, approximately 8% of the total area, gives rise to nearly 25% of the total production.

In all, 108 observations were used for determining chlorophyll distribution at the surface (Fig. 14). The regions of high concentrations are off Oman and Yemen and in the coastal

Table 8. Seasonal changes in the phytoplankton production in the northern Arabian Sea. Surface production is in $\text{mg C m}^{-3} \text{ day}^{-1}$ and column production in $\text{mg C m}^{-2} \text{ day}^{-1}$

Depth	Season	Minimum	Maximum	Average	sd
Surface	Premonsoon (Feb–May)	0.20	280.70	18.86	35.658
	SW Monsoon (June–Sept)	0.80	23.60	7.00	7.968
	NE Monsoon (Oct–Jan)	0.70	280.70	25.19	41.424
Column	Premonsoon (Feb–May)	17.0	6010.00	733.12	947.945
	SW Monsoon (June–Sept)	100.0	2223.00	921.33	1140.097
	NE Monsoon (Oct–Jan)	13.0	5790.0	919.04	1030.853

waters of Bombay and Gujarat. The rest of the area has less than 0.5 mg m^{-3} (Fig. 14). The average surface value for the northern Arabian Sea is 0.47 mg m^{-3} . In other words, the instantaneous production of chlorophyll in the entire area (within 1-m depth) would be 0.83×10^3 tonnes. Of this, the production in the coastal waters would be 0.80 mg m^{-3} , nearly 50% of the total chlorophyll content of the northern Arabian Sea. For the entire sea, the average surface chlorophyll has been reported to be 0.244 mg m^{-3} (QASIM, 1978). The contribution of the northern Arabian Sea to the total sea is about 50%.

Integrated values of chlorophyll between 0 and 50 m, (128 observations) are shown in Fig. 15. The overall picture is similar to that at the surface. The principal difference is that the

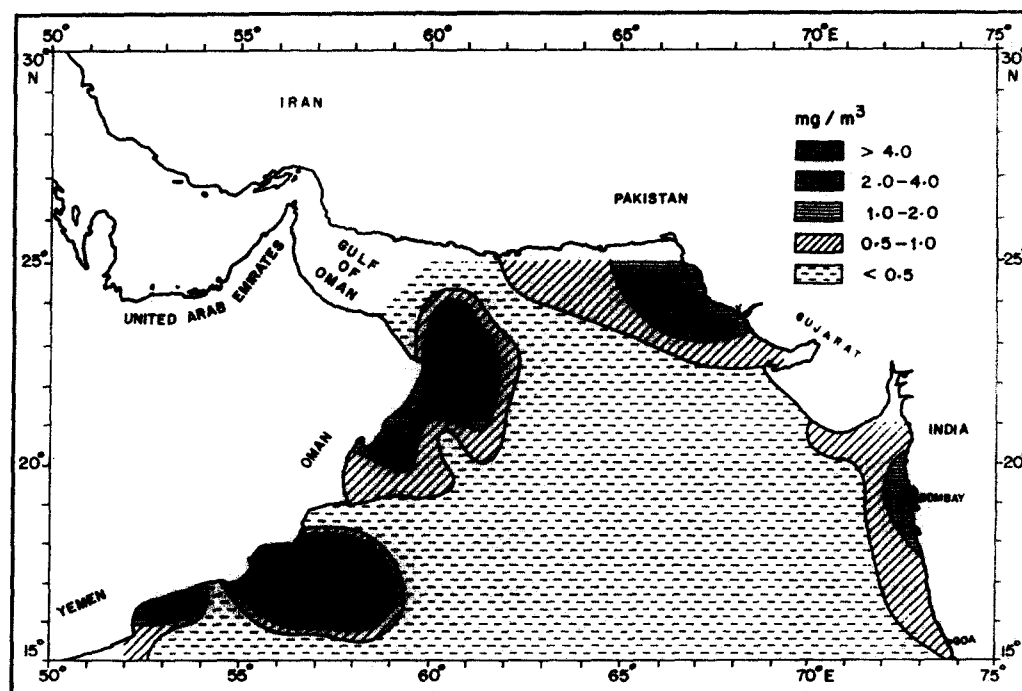


Fig. 14. Distribution of chlorophyll *a* at the surface of the northern Arabian Sea.

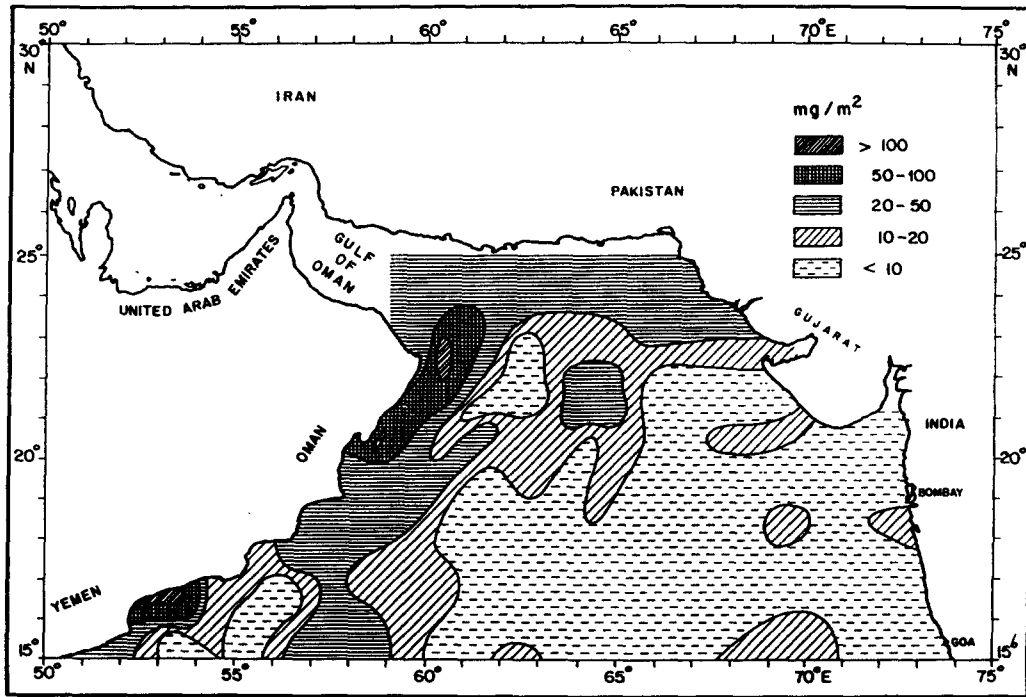


Fig. 15. Distribution of chlorophyll *a* in the upper 50 m of the northern Arabian Sea.

large region in Fig. 14 with less than 0.5 mg m^{-3} is broken into smaller areas with higher concentrations (Fig. 15), indicating that much of the chlorophyll occurs below the surface. Regions where the column chlorophyll is less than that at the surface signify that much of the chlorophyll occurs at the surface. The average in the 0 to 50-m column is 17.35 mg m^{-2} . In terms of instantaneous production in the whole area it would be $\sim 30 \times 10^3$ tonnes or 32% of the total instantaneous chlorophyll production in the Arabian Sea. The average value of chlorophyll *a* in the coastal waters is 26.76 mg m^{-2} , $\sim 15 \times 10^3$ tonnes, which indicates that about 50% of the total chlorophyll production in the northern Arabian Sea occurs in coastal waters.

From the results of ^{14}C uptake and distribution of chlorophyll *a* summarized above, it is clear that the northern Arabian Sea is probably the most fertile area. Nearly 50% of the total primary production of the entire Arabian Sea takes place in only about 25% of the area; about 8% of the total area of the Arabian Sea, the coastal waters of the northern Arabian Sea, sustains about 25% of the total production. Presumably for this reason a high rate of denitrification occurs at intermediate depths of the northern Arabian Sea.

Zooplankton biomass

The distribution of five different zooplankton biomass classes is shown in Fig. 16, which is based on 308 measurements. The range in the biomass was from 0.01 to 2.80 ml m^{-3} . The areas of high biomass were in the coastal waters of India, Pakistan, Oman, and Yemen.

From the biomass distributions published by IOBC (1968), the average for the whole Arabian Sea is 12.5 ml m^{-2} (200 to 0 m). The average for the northern Arabian Sea is

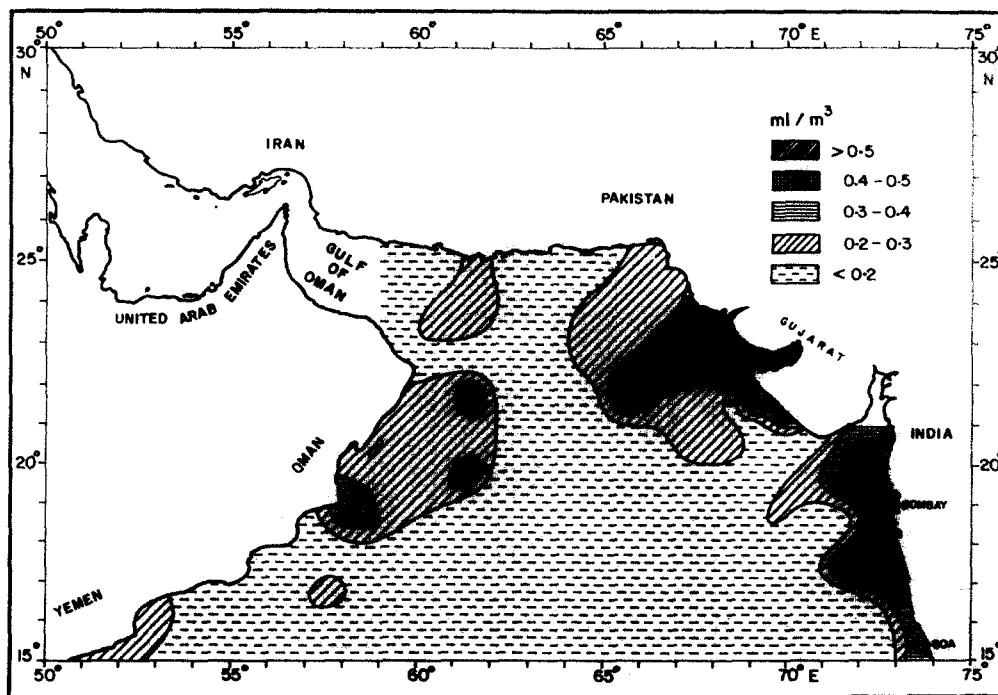


Fig. 16. Distribution of zooplankton biomass in the northern Arabian Sea.

50 ml m^{-2} , nearly four times that of the Arabian Sea. The average for coastal waters of the northern Arabian Sea is 62 ml m^{-2} . The biomass of the coastal waters is about 40% of the total of the northern Arabian Sea or about 20% of the total for the entire Arabian Sea. During the fourth cruise of INS *Darshak*, a record value of zooplankton biomass (2.80 ml m^{-3}) was obtained on 20 March 1974 at $22^{\circ}4.2'N$, $67^{\circ}15'E$ (PAULINOSE and ARAVINDAKSHAN, 1977). The sample was largely luminous ostracods (*Cypridina* sp.).

The highest zooplankton biomass recorded during the IIOE was 187 ml m^{-2} (0.93 ml m^{-3}) off the Somali coast (IOBC, 1969). Between $20^{\circ}N$ and the Gulf of Oman, LENZ (1973) reported the highest value of zooplankton biomass during the *Meteor* cruise, and according to him "near the Gulf of Oman the zooplankton is on average four times as abundant". Another interesting feature of the vertical distribution of zooplankton is the greater abundance in the top 200 m than in greater depths, i.e., between 900 m and the surface. No significant difference in the biomass was observed between the hauls taken from 200 to 0 m and 900 to 0 m (PAULINOSE and ARAVINDAKSHAN, 1977), indicating that the organisms are largely confined to the upper 200 m and they tend to avoid the oxygen-deficient layer below 200 m. Almost all the samples contained copepods and chaetognaths, ostracods were in 90% of the samples, amphipods and decapods in 89%, and siphonophores in about 87%. Euphausiids were identified in about 87% and polychaetes in 80% of the samples. Other organisms were appendicularians (in 70%), pteropods (in 60%), bivalves (in 40%), fish eggs (in 12%), scyphozoan, cumaceans, and stomatopods (in about 5%), ctenophores (in 3%), cirripedes (in 1.5%), and isopods and phyllosomans (in about 0.5%).

Benthic biomass

The distribution of benthic biomass is shown in Figs 17 and 18. The macrobenthos distribution (Fig. 17) is based on 143 samples, and that of the meiobenthos on 64 samples (Fig. 18). Macrobenthos in the depth range 0 to 200 m varied from 0.15 to 153.20 g m⁻² (average 6.74 g m⁻²). At greater depths (200 to 1000 m), the range in biomass was from 0.15 to 10.56 g m⁻² (average 4.24 g m⁻²) and at depths greater than 1000 m it ranged from 0.35 to 12.59 g m⁻² (average 2.70 g m⁻²). The values indicate that macrobenthos biomass progressively decreases with increasing depth. There was also a distinct latitudinal variation (Fig. 17). Maxima were generally close to the shore and between 23 and 24°N and minimum values were generally offshore and between 15 and 16°N. The region between 16 and 20°N was also rich in macrobenthos (Fig. 17). Similar differences in the shelf region of the northeastern Arabian Sea were reported by PARULEKAR and WAGH (1975). Polychaetes constituted about 60% while bivalves (20%) and crustaceans (15%) were the other major components.

Meiobenthos, on the other hand, showed different relationships and was greater than the macrobenthos. In the shelf region (0 to 200 m), the meiobenthic biomass ranged from 0.02 to 14.74 g m⁻² (average 12.64 g m⁻²). Between 200 and 1000 m the meiobenthos ranged from 2.01 to 42.30 g m⁻² (average 39.34 g m⁻²) and at depths greater than 1000 m, the range was 16.55 to 119 g m⁻² (average 49.10 g m⁻²). It is thus clear that the average biomass increased with increasing depth. Nematodes and foraminiferans were the major components of the meiofauna and harpacticoid copepods, polychaetes, and turbellarians were minor components.

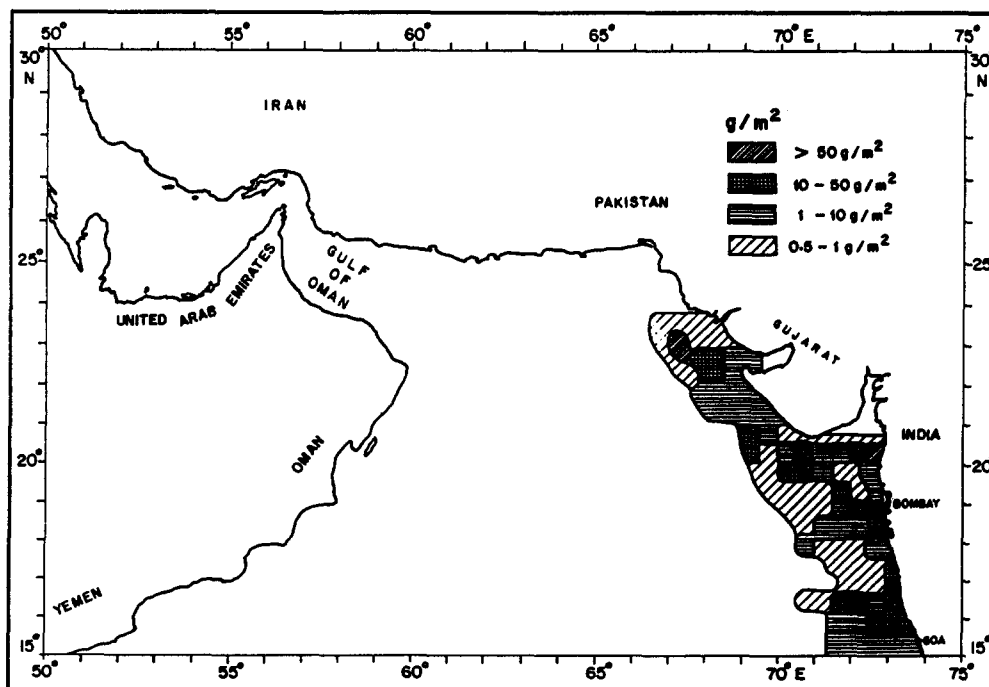


Fig. 17. Distribution of benthic macrofauna in some parts of the coastal regions of the northern Arabian Sea.

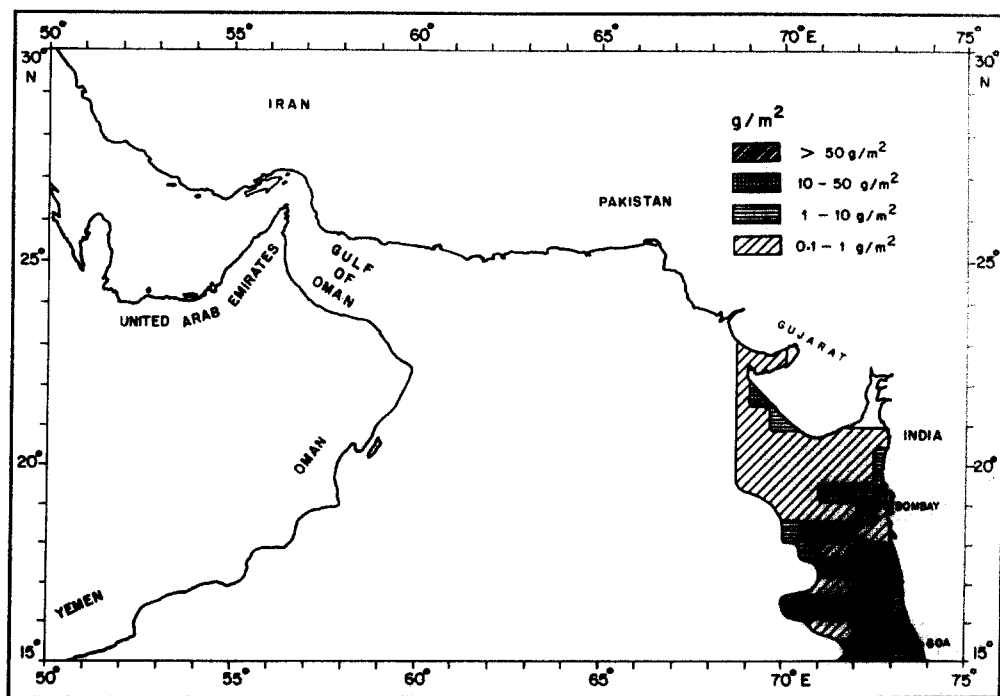


Fig. 18. Distribution of benthic microfauna in some parts of the coastal waters of the northern Arabian Sea.

Dissolved oxygen at 1000 m varies between 0.3 and 1 ml l⁻¹ (Fig. 6). At this depth the meiobenthos biomass increases. This indicates that organisms such as nematodes, foraminiferans, harpacticoid copepods, polychaetes, and turbellarians, which are abundant at that depth, have low metabolic oxygen requirements. Experiments on several species have indicated that many organisms belonging to the meiofauna live in poorly-oxygenated water (TIETJEN, 1969).

The range in total benthic biomass (macro and meio combined) was from 0.014 to 153.20 g m⁻² (average 8.57 g m⁻²). At this average, the total benthic biomass in the entire shelf area of the northern Arabian Sea (0.2×10^6 km²) would be about 2×10^6 tonnes.

A comparison of the benthic biomass with that of other known areas of the Indian Ocean indicates that the northern Arabian Sea is relatively poor in benthos. In the southern Arabian Sea between 15 and 8°N, the average benthic biomass is 31.0 g m⁻² (HARKANTRA, NAIR, ANSARI and PARULEKAR, 1980) and in the Bay of Bengal the average is 18.50 g m⁻² (ANSARI, PARULEKAR, HARKANTRA and NAIR, 1977). The average, 8.57 g m⁻², for the northern Arabian Sea is close to that of the Andaman Sea, where the mean biomass has been reported to be 9.60 g m⁻² (A. H. PARULEKAR, personal communication). Presumably the low benthic biomass in the northern Arabian Sea is because of its low oxygen content.

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