

Distribution of Inorganic Phosphate in the Upper Hundred-Metre Column in Different Regions of the Northern Indian Ocean

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Based on the data collected by the research vessels, Discovery (UK), Vityaz (USSR), Anton Bruun (USA), and INS Kistna (India), during the International Indian Ocean Expedition Programme (1960-65), season-wise concentrations of the available phosphate in the upper 100 m in the different regions of the northern Indian Ocean were reported. Peripheral regions both of the Arabian Sea and the Bay of Bengal showed higher concentrations, while the central and equatorial regions remained relatively poorer during the NE and pre-monsoon seasons. During the SW monsoon, the concentrations increased in almost all the regions, and this rising trend was maintained during months immediately following it. Maximum concentrations (5.3 g/m³) were observed in waters off the Oman and Iran coasts and slightly less in waters off Pakistan and west coast of India during the post-monsoon months. The computed phosphate data of the respective regions when compared with the primary productivity and the plankton biomass data showed no direct relationship with the former but agreed more closely with the latter, though qualitatively if not quantitatively. In general, the pattern of distribution conforms broadly with that of the highly productive areas of the northern Indian Ocean.

PHOSPHORUS, one of the important biogenic elements connected with the economy of the sea, occurs both in the reactive (inorganic phosphate) and unreactive (organic phosphorus) states. The two forms are intimately associated with each other as well as with the biochemical circulation in the sea. During photosynthetic activity the inorganic fraction gets converted into the organic form and incorporated into the cells of the organisms. After the organisms die and sink to great depths, processes of decay and decomposition convert the organic phosphorus back into the inorganic form. A knowledge of this phosphorus cycle in different regions of the ocean, with particular reference to both the utilization and regeneration of this element, will help in the characterization of productive and non-productive areas of the ocean. Harvey² while discussing the phosphorus cycle has indicated the possibility that, apart from the role of the bottom muds in the turnover and regeneration of the phosphorus, there are areas where some amount of regeneration takes place in the upper layers itself. Maximova³ observed that the regeneration at the upper levels takes place to the extent of about 35%. Such a regeneration has been shown to occur within the upper 75-100 m of the ocean, which includes in general the mixed layer and layer of sharp density gradient (thermocline). It is, therefore, considered worth while to obtain an estimate of the total available phosphate in this column of 100 m, which, apart from providing a valuable index to the productivity potential of the region under study, will also help in furthering our knowledge of the actual regenerative processes within the upper layers.

Previous work in the Indian Ocean with particular reference to phosphate distribution in the seas around India is concerned mostly with the coastal and near-shore waters⁴⁻¹³. It was only during the

International Indian Ocean Expedition (IIOE, 1960-65) that several areas of the Indian Ocean have been covered by research ships belonging to different countries and a large amount of routine hydrographical data were collected by most of the ships. Data relating to nutrient distribution in the shelf waters off the west and east coasts of India collected by the participating Indian ships, INS Kistna and RV *Varuna*, have been presented¹⁴⁻¹⁷, but these again relate to a few selected regions and restricted to one or two seasons only. Recently by exchange arrangement with the World Data Centres A & B, the National Institute of Oceanography (Indian National Oceanographic Data Centre) has been able to obtain oceanographic station data in respect of cruises conducted by various countries in the northern Indian Ocean. The present paper is based on the analysis of data collected by the oceanographic ships, RRS *Discovery* (UK), RV *Vityaz* (USSR), RV *Anton Bruun* (US) and INS *Kistna* (India), in this part of the Indian Ocean.

Materials and Methods

Data relating to phosphates were compiled from the oceanographic station lists of the above ships. Where the data for actual depths were not available, data for interpolated depths were utilized. The total available integrated phosphate between surface and 100 m was calculated taking into account the concentrations against individual depths and integrating them according to the formula:

$$TC_{100}^{\text{total conc.}} = (d_{10} - d_0) \times \frac{(a_{10} + a_0)}{2} + \dots + (d_{100} - d_{75}) \times \frac{(a_{100} + a_{75})}{2}$$

where d is depth in metres and a is conc. of $PO_4\text{-P}$ as mg/m^2 . The formula used is similar to that of

Viswanathan and Ganguly¹⁷ but with the difference that while they have computed the integral mean concentration (IMC) we have calculated the total concentration.

The computed data are then grouped into the following seasons, for the purpose of study and comparison: (i) north-east monsoon, December to February; (ii) pre-south-west monsoon, (summer season) March to May; (iii) south-west monsoon, June to August; and (iv) post-south-west monsoon, September to November.

Taking 5" square as a basic unit area, the average concentrations of such regions wherein sufficient data for averaging were available were calculated. However, in certain sections having relatively low density of data, larger areas involving more than one five-degree grid have been taken into consideration and the overall means have been included in the table and discussed.

Results

Computed values for the total available phosphate below 1 sq m of the sea surface in 100 m column in different regions of the northern Indian Ocean during different seasons are given in Table 1. Density of data available during the different seasons is given in Fig. 1. It is to be pointed out here that there has not been a full coverage of all the regions in all the seasons of the year. The inference drawn from the rather inadequate data from a few regions should not, therefore, be taken as truly representative for the whole region. But in view of the fact that some of the regions, particularly at the margins, of both the Arabian Sea and the Bay of Bengal, have been covered satisfactorily, a discussion of the distribution of phosphate in these regions has a greater relevance to the problem of productivity.

Fairly high amounts of phosphates are available along the western margins of both the Arabian Sea and the Bay of Bengal (Table 1). Highest value is seen (5.6 g/m²) off the Madras coast. Both in the north-western part of the Arabian Sea and towards the head of the Bay of Bengal the values are high (maximum, 2.6-3.5 g/m² and mean values lie between 1.2 and 2.2 g/m²). The concentrations tend to diminish as the equator is approached.

In pre-SW, monsoon a similar feature is seen in the northern Arabian Sea, where an average value or 2.2 g/m² has been obtained off the coast of Arabia. The value is found to be below 1.6 g in the rest of the regions. In the Bay of Bengal where a maximum of the order of 3.5 g/m² has been recorded at the head of the Bay, the mean available phosphate is seen to be much less, showing thereby that the overall availability is poor. Only off the Burma and Thailand coasts, there is an appreciable high concentration of phosphate in the whole column and the values range between 1.7 and 2.6 g/m².

As is the case with other parameters, the onset of the south-west monsoon has a marked influence in the phosphate distribution. From the computed data it may be seen that the north-western Arabian Sea and part of the Andaman Sea regions have high concentrations of available phosphate (Table 1), showing a considerable degree of enrichment.

The north-western part of the bay, off the Visakhapatnam coast and the head of the Bay of Bengal, also shows evidence of enrichment, the mean values having the same order of magnitude as in

the Andaman Sea and off Thailand coast, although the highest concentrations reached are not similar. Maximum enrichment is seen in the north-western Arabian Sea, off the Somalia and Arabian coasts, which is a well-known upwelling region. As in the other seasons there is less of phosphate in the equatorial regions.

The concentrations of phosphate obtained during the onset of SW monsoon continues to have an upward trend -not only during the entire monsoon period but also during the post-monsoon months (Table 1). In the north-western Arabian Sea, the highest values have been obtained during this period. The maximum available phosphate is 5.3 g/m² (mean conc. of 4.1 g/m²) in the waters off the Oman and Iran coasts. The high values persist in the north-eastern Arabian Sea also, but they are slightly lower, the maximum and mean being respectively 4.0 and 3.0 g/m². While there is not much change in the conditions off the Somalia coast, considerable impoverishment has been observed in the equatorial region, both in the Arabian Sea and the Bay of Bengal sections.

Discussion

One of the main objectives of the present study is to obtain an idea of the productivity potential of the waters of this part of the Indian Ocean from considerations of nutrient distribution, particularly from data concerning the available phosphate in the upper 100 m in different areas. It is, however, to be stated that in view of the fact that this 100 m layer includes both the euphotic zone and the thermocline and also as there is considerable variability in the thickness of the euphotic zone from region to region and from season to season, it would not be possible to arrive at any quantitative relationship from the data on available phosphate alone in the upper 100 m. The data are, no doubt, useful in providing a qualitative index of the productivity potential. It would also be possible to show that given other conditions such as light, favourable temperature and stability of the water masses, the areas having very high concentrations of phosphate in the upper 100 m would support high organic production.

The results presented and discussed in the previous section are, therefore, examined against this background. It may be seen that both in the Arabian Sea and the Bay of Bengal high concentrations of phosphate occur in the peripheral regions while the central portions are relatively poorer; In most of these areas, high concentrations are associated with south-west monsoon and the months immediately following it. The concentrations are, in general, lower during rest of the months. Thus, meteorological and physical conditions play a very important role in regulating the distribution of the nutrients. Bushinski¹⁸ had stated that higher concentrations of phosphate in the upper strata of water are either caused by vertical movement of deeper water towards the surface by processes of upwelling or by discharge of fresh waters from the rivers into the sea. It has been shown that the contribution by land drainage or river outflow does not account for much of the inorganic phosphate in the upper layers of the sea. The bulk of the supply has to come from the subsurface levels. It is also to be taken into account that in the offshore

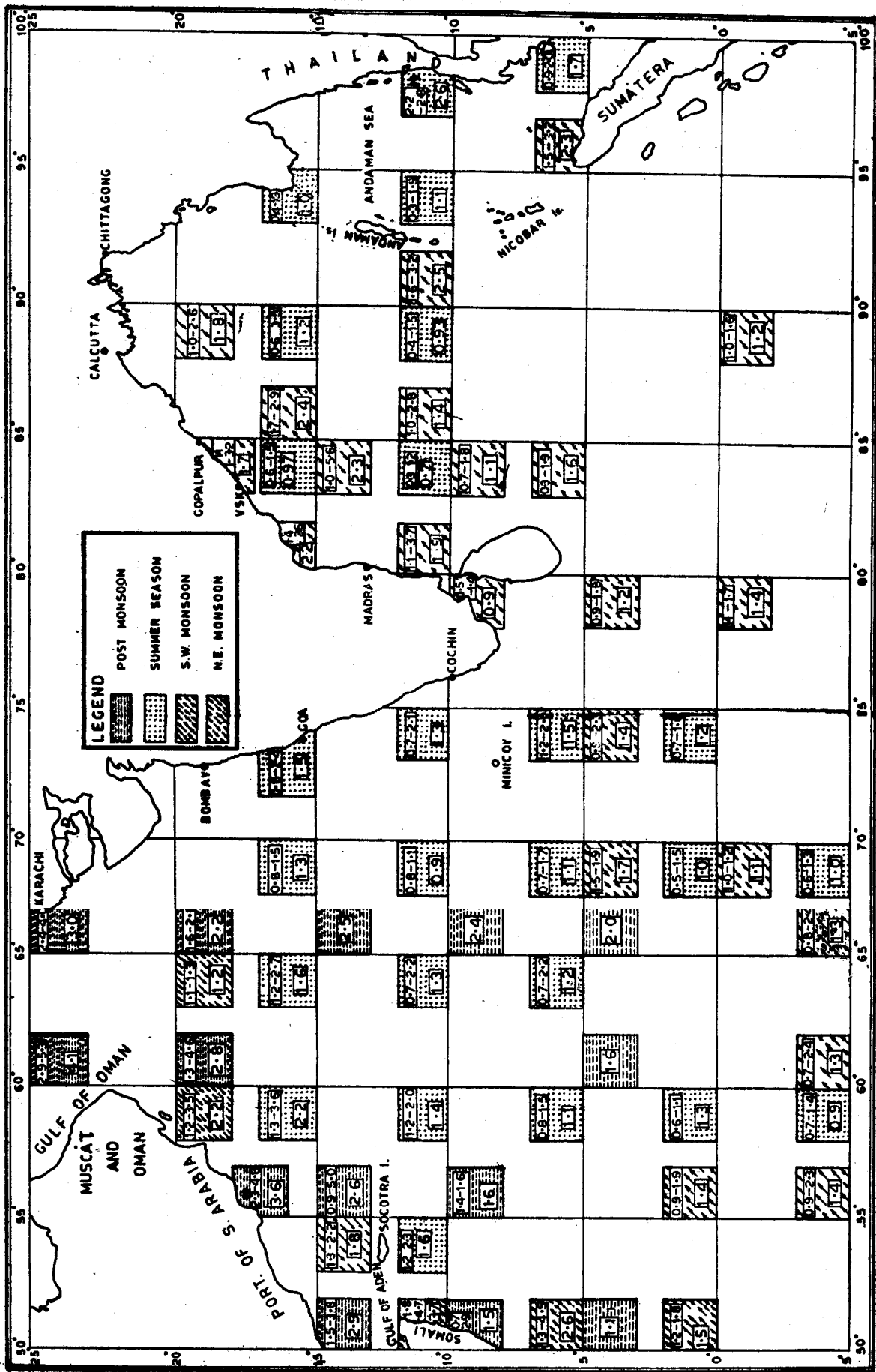


Fig. 1 — Average concentrations of inorganic phosphate in upper 100 m [For explanation see text]

TABLE 1—TOTAL AVAILABLE PHOSPHATE IN 100 M COLUMN BELOW 1 SQ M OF THE SEA SURFACE IN THE NE MONSOON (DECEMBER-FEBRUARY), PRE-SW MONSOON (MARCH-MAY), SW MONSOON (JUNE-AUGUST) AND POST-SW MONSOON (SEPTEMBER-NOVEMBER)

NW Indian Ocean (Arabian Sea)				NE Indian Ocean (Bay of Bengal)			
Region	PO ₄ -P, g/m ³			Region	PO ₄ -P, g/m ³		
	Max.	Min.	Mean		Max.	Min.	Mean
NE MONSOON							
Off Arabian coast, 15-20°N; 55-60°E	3.5	1.2	2.2	Head of Bay of Bengal and off Gopalpur (Indian coast)	2.6	1.0	1.8
N. Arabian Sea, 15-20°N; 60-65°E	1.3	1.1	1.2	Off Visakhapatnam (Indian coast)	3.2	1.1	1.7
N. Somalia region and in the vicinity of Socotra Is., 10-15°N; SO-55°E	2.2	1.3	1.8	Off Madras (Indian coast)	5.6	1.0	2.3
West of Ceylon and off the southern part of Indian peninsula, 5-10°N; 75-80°E	1.4	0.5	0.9	East of Ceylon, 5-10°N; 80-85°E	1.8	0.7	1.1
On either side of the equator between 65° and 80°E meridian	2.3	0.9	1.4	Equatorial region between 85° and 90°E meridian	1.6	1.0	1.2
PRE-SW MONSOON							
Off Arabian coast, 15-20°N; 55-60°E	3.6	1.3	2.2	Head of Bay of Bengal and off Gopalpur (Indian coast)	3.5	0.6	1.2
C. Arabian Sea, 15-20°N; 60-70°E	2.7	0.8	1.45	Off Visakhapatnam	1.5	0.6	0.97
Off Indian central west coast, 15-20°N; 70-75°E (Bombay-Goa region)	2.4	0.8	1.5	Off Burma coast, 15-20°N; 90-95°E	1.9	0.4	1.0
W. Arabian Sea, N. Somali and Socotra region, 10-15°N; 50-55°E	2.3	1.2	1.6	Off Madras (Indian coast)	1.2	0.3	0.7
S. Arabian Sea, 5-10°N; 55-75°E	2.2	0.7	1.2	Southern part of Bay of Bengal between 85° and 100°E (max. in the eastern part of the Andaman Sea)	2.8	0.3	1.5
Equatorial Indian Ocean between 55° and 75°E	1.4	0.6	1.1	West of Thailand coast (off Phuket), 5-10°N; 95-100°E	2.0	0.9	1.7
SW MONSOON							
N. Somalia and Socotra region, 10-15°N; 50-55°E	4.7	1.8	3.7	Head of Bay of Bengal	2.9	1.7	2.4
Off C. Somalia coast, 5-10°N; 50-55°E	4.5	1.3	2.6	Off Visakhapatnam (Indian coast), 15-20°N; 80-85°E	2.6	1.4	2.2
Off S. Somalia coast, 0-5°N; 55-60°E	1.8	1.2	1.5	Off Madras (Indian coast)	3.7	1.1	1.9
Equatorial region between 55° and 70°E meridian	2.4	0.7	1.35	Andaman Sea, 10-15°N; 90-95°E	3.2	1.6	2.5
Off Thailand coast, 5-10°N; 95-100°E					3.2	1.5	2.3
POST-SW MONSOON							
NW Arabian Sea off Oman and Iran coasts, 20-25°N; 60-65°E	5.3	2.9	4.1	Off Madras (Indian coast) (along 13°N only)	—	—	2.0*
NE Arabian Sea, 20-25°N; 65-70°E, off Pakistan and Indian coasts	4.0	2.4	3.0	Andaman Sea (along 13°N only)	—	—	2.0*
N. Somalia and Socotra region (W. Arabian Sea), 10-15°N; 50-55°E	3.8	1.5	2.9	West of Nicobar Island (along 92°E only)	—	—	1.5*
Off C. Somalia coast, 5-10°N; 50-55°E	2.9	0.7	1.5	Equatorial region (along 92°E only)	0.8	0.6	0.7*
C. Arabian Sea, 10-20°N; 55-70°E	4.8	0.9	2.7				
S. Arabian Sea, 5-10°N; 55-70°E	2.4	1.6†					
Equatorial region between 50° and 75°E meridian	2.0	1.1†					

*Values being too few and along one particular latitude/meridian have not been shown in Fig. 1.
 †Values being too few, means not calculated.

waters, a certain amount of regeneration of phosphate takes place in the upper layers from the dying and decaying organic matter and this could contribute a substantial amount of phosphate to the upper layers of the sea.

Ryther and Menzel¹⁹ have shown the presence of upwelling in the Somali-Arabian region during the south-west monsoon. The presence of upwelled waters has also been detected off the Oman, Iran and Pakistan coasts during the prevalence of the south-west monsoon. Similarly other workers²⁰⁻²⁵ have shown that upwelling processes bring sub-surface waters to upper levels along the south-west coast of India, during the late south-west monsoon and early post-monsoon. Jayaraman and Gogate²⁶ have indicated the possibility of upwelling north of Bombay and off the Gulf of Cambay during the north-east monsoon period. The phosphate data compiled from the present study provide additional support to these early findings.

Similarly in the Bay of Bengal, off the Visakhapatnam and Madras coasts, upwelling has been shown to cause enrichment of upper layers during the south-west monsoon period^{27,28}. The early cruises of the US research vessel *Anton Bruun* have been able to locate upwelling areas in the Bay of Bengal off Burma and Thailand coasts and the Andaman Sea also during the south-west monsoon period. Zernova and Ivannov²⁹ have observed from productivity measurements that the Andaman Sea region of the Bay of Bengal has the highest production.

Primary production measurements carried out in the different areas of the Arabian Sea during the IIOE have given a wide range of values. Ryther and Menzel¹⁹ have obtained in a few stations off the Gulf of Oman values of the order of 5.7 to 6.4 g carbon fixed/m²/day. On the other hand, in central Arabian Sea between 60° and 80°E, the magnitude of production has been shown to be low, the values range between 0.26 and 0.50 g C/m²/day³⁰. Prasad³¹ has obtained rates of primary production of 2.0 g/m²/day near the coast of Cape Comorin, but only 0.20-0.50 g/m²/day outside the shelf in the same area. Radhakrishna³² working in the shelf off Alleppey on the south-west coast of India has obtained production rates of 0.81 g/m²/day. In a transect occupied by RV *Anton Bruun* in the central Arabian Sea between Aden and Bombay in the spring of 1963, the primary production rates have been found to be between 0.07 and 0.29 g/m²/day. In order to provide a comparison between the available phosphate in a 100 m column and the rate of primary production, the data obtained for this transect occupied by RV *Anton Bruun* are as follows:

Station No.	Position		PO-P in 100 m column gP/m ²	Primary production gC/m ² /day
	Lat., N	Long., E		
1	12°00'	45°55'	1.21	0.07
2	12°00'	48°00'	1.15	0.29
3	12°02'	50°00'	1.34	0.21
4	13°34'	52°00'	1.63	0.28
5	14°04'	54°11'	1.96	0.16

It may be seen from the above comparison that there is no direct relationship between the available phosphate and the rates of primary produc-

tion. The possible reason for this lack of relationship has already been explained earlier in this section.

If, however, we examine the data in respect of plankton biomass³¹ with the data on the available phosphate in the 100 m column, it would, perhaps, be possible to obtain a much closer relationship. This again would be qualitative and no quantitative correlations can be established.

During the SW monsoon, the waters in the western half of the Arabian Sea and off the south-western coast of India have a higher biomass (>50 ml) based on displacement volumes while in the central zone and in the waters off the Gujarat coast it is much lower. For the same period, the plankton biomass in the Bay of Bengal has a low value (10-20 ml). The Andaman Sea maintains a medium biomass of about 20 ml.

In the north-east monsoon season, the plankton distribution in the Arabian Sea becomes somewhat diffuse. The marked low production zone in the central part of the Arabian Sea disappears during this period. The coastal region south of Somalia towards the equator registers a small increase in the plankton biomass. Fairly high biomass is seen only around the Gulfs of Aden and Oman and the coastal region of Somalia. Thus the highly productive areas are found around Somalia and Arabian coasts and to a certain extent off the south-west coast of India, conforming broadly to the pattern of distribution of the total available phosphate in the upper 100 m.

In conclusion, it is stated that in order to arrive at a proper quantitative evaluation of the nutrient availability and the productivity potential in the different regions of the marine environment, it would be necessary to (i) get exact measures of the thickness of the mixed layer and the euphotic zone; (ii) work out the nutrient budget within this zone; and (iii) estimate the magnitude of production in the customary manner up to the limit of light penetration.

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