

CLIMATE OF THE NORTHERN INDIAN OCEAN AND ASSOCIATED PRODUCTIVITY

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Abstract : The climatic factors likely to influence the phytoplankton production in the northern Indian Ocean are examined. The major cause for the high productivity of the Arabian Sea is the nutrient enrichment of the euphotic zone by upwelling especially off the coasts of Somalia, Arabia and the south west coast of India. In Bay of Bengal, the major factor influencing high primary production is the estuarine type of circulation in the northern part. The main features in the distribution of the chlorophyll *a* and primary production are the high values in the northern and western parts of the Arabian Sea and also along the southern tip of India during May to October. During the period November to April, chlorophyll *a* is relatively high in the northern Arabian Sea and north eastern parts of Bay of Bengal.

Résumé : Le bilan radiatif net due aux radiations d'ondes courtes recues à la surface de la Mer d'Oman est légèrement plus élevé que celui du Golfe du Bengale et les différences des taux de productivité primaire dues aux inégalités des radiations incidentes seraient marginales. Un phénomène d'upwelling à grande échelle existe dans la Mer d'Oman près des côtes de Somali, d'Arabie et de la côte Sud-Ouest de l'Inde. Les régions septentrionales du Golfe du Bengale ont un modèle caractéristique des zones d'estuaires. Une étude de la chlorophylle-*a* et la répartition de la productivité primaire montre des valeurs élevées dans les régions occidentales et septentrionales de la Mer d'Oman et également près de la pointe Sud de l'Inde de Mai à Octobre. De Novembre à Avril, la chlorophylle-*a* est surtout élevée dans la partie septentrionale de la Mer d'Oman et la partie nord-est du Golfe du Bengale.

Resumen : La ganancia neta de radiación de onda corta en la superficie del mar Arábigo, es ligeramente mayor que en la Bahía de Bengala aunque las diferencias de productividad primaria entre las dos podrían ser mínimas. Inversiones a gran escala ocurren en el mar Arábigo a lo largo de la costa de Somalia, Arabia y suroeste de la India. El área norte de la Bahía de Bengala tiene características estuarinas. El estudio de la distribución de clorofila-A y la productividad primaria, mostró de mayo a octubre, altos valores en el norte y occidente del mar Arábigo y extremo sur de la India. Sin embargo de noviembre a abril la concentración de clorofila es más alta en el norte del mar Arábigo y noroeste de la Bahía de Bengala.

Key Words : North Indian Ocean, climate, oceanic response, nutrient enrichment, primary production

INTRODUCTION

The marine environment is a dynamic realm with complex ecological patterns. Classification of all ecosystems are based on the production of organic matter by photosynthesis and the capacity of a region to support higher trophic levels. The production of organic matter is primarily controlled by the quantum of available radiant energy and on the nutrient concentration in the euphotic zone. While the incident solar energy is dependent on the geographical location and cloudiness, the availability of inorganic nutrients depends on several climatic parameters like winds, circulation and mixing processes in the sea. Temperature which controls the metabolism and salinity which regulates the osmotic

pressure of the organisms are again determined by the climatic features. With an abundant supply of carbon dioxide in the marine environment, climate controls the quality of the ecosystem.

Herein, the authors present a classification of the northern Indian Ocean based on the nutrient enrichment of the euphotic zone which results as the ocean responds to the variable climatic elements like insolation, winds, and rainfall.

CLIMATIC FACTORS

RADIATION

It is well recognised that the availability of photosynthetically active radiation (visible part of the solar spectrum, ranging from 400 to 700 nm) is one of the limiting factors for photosynthesis. There are several studies relating the quantum of primary production to irradiance. The typical response curve shows a steep rise in photosynthesis as the irradiance increases to $20-30 \text{ W m}^{-2}$. Further increase in the irradiance does not substantially increase the rate of production. On the other hand, excessive irradiance at the surface, according to some workers, inhibits photosynthesis.

The quantum of short wave radiation incident at the sea surface over the northern Indian Ocean increases from winter to summer season. With the onset and advance of the south west (SW) monsoon and clouding over extensive areas, the incoming radiation decreases much below the winter levels. The short wave radiation along the west coast of India is about 200 W m^{-2} in January, while it is only about 140 W m^{-2} in July. The incoming solar radiation decreases from west to east in the Arabian Sea during the SW monsoon season. By October, with less clouding over the area, a slight increase in short wave radiation is observed. In general, radiation received in the Bay of Bengal is marginally less than that in the Arabian Sea (Hastenrath and Lamb 1979).

The radiation levels in the northern Indian Ocean far exceed the optimum light intensity. As the light penetrates into the water column, the optimum intensity is reached at the sub surface levels. Therefore, radiation will not be a factor limiting primary productivity of this region and in fact the higher intensities slightly inhibit productivity at the surface.

SURFACE WINDS

The basic feature of wind distribution over the northern Indian Ocean is the reversal of the wind systems known as monsoons (Fig. 1). Steady northerlies or north-easterlies prevail in the oceanic area during winter (December to February) and westerlies or south-westerlies during summer (June to September). In contrast, during transition periods of March to May and October to November the winds are weak and unsteady. Strong winds with speeds exceeding 15 m sec^{-1} are observed off the African and Arabian coasts during SW monsoon period. The wind speeds gradually decrease towards the Indian coast. The region of maximum wind speed extends from the Somali coast, across the Arabian Sea to the central west coast of India. Winds are marginally weaker in the Bay of Bengal during SW monsoon. During winter the wind speeds are about 7 m sec^{-1} in the western Arabian Sea and about 5 m sec^{-1} in the south central Bay of Bengal (Hastenrath and Lamb 1979).

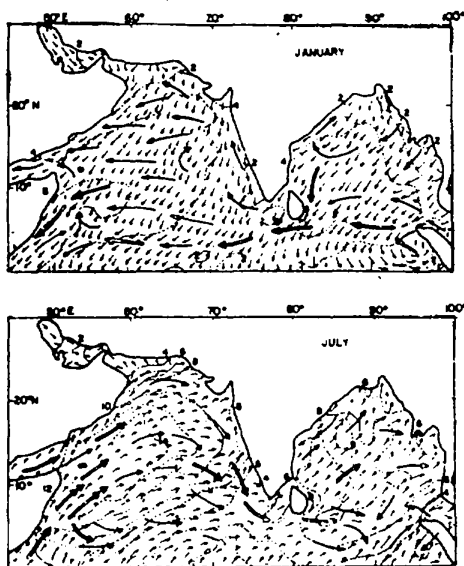


Fig. 1. Surface wind and current patterns in the northern Indian Ocean during winter and summer. The long arrows represent the surface currents. The contours represent wind speeds ($m\ sec^{-1}$), and the small arrows, the wind direction.

PRECIPITATION OVER THE INDIAN SUB CONTINENT

The south-west monsoon sets in along southern tip of India by the first week of June and progressively moves north covering the entire Indian sub-continent by mid July. The Western Ghats, the sub Himalayan regions and the western Burma hills receive very high rains. Monsoon depressions form in the northern Bay of Bengal and move in a westerly or northwesterly direction and this results in good rains over the eastern and central parts of India. During the north east (NE) monsoon season, the east coast of India and some parts of south India receive moderate rains. Indus and a few minor rivers on the west coast of India empty into the Arabian Sea, while the major rivers, viz., Ganges, Brahmaputra, Iravathi, Mahanadi, Godavari and Krishna, empty into the Bay of Bengal.

OCEANIC RESPONSE

UPWELLING

Upwelling is essentially the upward component of the field of motion and is an important process for transfer of the cold nutrient rich sub surface water into the euphotic zone. Upwelling in the ocean can be either due to thermohaline processes or due to wind induction. Thermohaline upwelling implies formation and sinking of cold water masses

in the polar regions and consequent upward movement near the equatorial regions. This process depends on the long range climatic factors and may not have much effect on the immediate productivity of any region, as the process is rather slow. On the other hand, upwelling induced by surface wind is very important since much of the transfer of sub surface nutrients takes place by this process. The wind induced upwelling may either be due to local forcing, or remote forcing. Upwelling can also result when the sense of coriolis acceleration of the coastal currents is offshore. Thus the pattern of wind distribution determines the pattern of surface circulation which in turn governs the level of nutrient concentration in the euphotic zone.

SURFACE CIRCULATION

The response of the ocean to the alternate forcing of monsoons is clearly reflected in seasonal variation in surface circulation (Fig. 1). The transition periods are characterised by weak and unsteady currents. The general circulation pattern resembles those of the other oceans during the NE monsoon period. However, during SW monsoon period the Somali current and the east flowing monsoon current replace the north equatorial current (see Anonymous 1960).

In the northern Indian Ocean, associated with the climatic wind patterns, wind induced upwelling takes place all along the western boundaries. In the Bay of Bengal, the south western region, adjoining the east coast of India are also favourable for upwelling. However, the influx of large quantities of fresh water into the region suppresses wind-induced upwelling along northern regions of the east coast of India. As a consequence of the southerly current off the west coast of India during SW monsoon period, nutrient rich sub surface water is brought up to the euphotic zone.

SEA SURFACE TEMPERATURE

The observed distributions of the sea surface temperature are the result of several processes associated with the transfer of heat in the interior of the ocean as well as across the sea surface. During winter, because of the flow of the continental airmass the sea surface temperatures in the northern Arabian Sea and Bay of Bengal are fairly low ($\approx 20^{\circ}\text{C}$). The surface temperature increases gradually to south. By April, the surface temperature over most part of the ocean is in the range of 27 to 29°C . During the SW monsoon period, a remarkable change in the surface temperature distribution takes place. Because of the development of the northerly Somali current and with strong south westerlies off the Somali coast, intense upwelling occurs off the Somali and Arabian coasts and the sea surface temperature is decreased considerably. The mean decrease in sea surface temperature is of the order of 5°C off the Somali and Arabian coasts and 2 to 3°C along the south west coast of India (Sastry and Ramesh Babu 1983). The main mechanism of cooling appears to be the mixing across the thermocline due to shear instability at the interface. The extent of cooling of the sea surface can be roughly taken as an indication of transfer of nutrients to the surface layer. Sastry and Ramesh Babu (1983) have shown that May minus July temperature is the largest ($\approx 4^{\circ}\text{C}$) along the Somali and Arabian coasts and about 2°C along the west coast of India. They have also suggested that the cold upwelled water spreads over an extensive area thereby enriching the surface layers with nutrients. By October, winds are again favourable for the development of North Equatorial Current and sea surface temperature returns to the winter pattern.

EVAPORATION AND PRECIPITATION

Over most of the regions of the northern Indian Ocean, the annual evaporation is about 2000 mm (Gorshkov 1978). However, there is a net loss of water over the northern Arabian Sea whereas the Bay of Bengal has excess precipitation over evaporation, except off the east coast of India. This contributes partially to the observed salinity pattern at surface and sub surface levels.

SURFACE SALINITY

The surface salinity is controlled mainly by evaporation, precipitation and fresh water discharges into an area. The surface salinity shows a rapid decrease with the advance of southwest monsoon (Wyrki 1971). It is about 30‰ over the northern Bay of Bengal and progressively increases southward. During winter, because of reduction of fresh water run off from the rivers, the salinity gradually increases. The low salinity water from equatorial region is transported westward into the Arabian Sea by the North Equatorial Current. Low salinity values are seen along the west coast of India during the southwest monsoon season. An examination of the topography of the 33.6‰ isohaline in late winter in the Bay of Bengal (Rao and Sastry 1981) shows that the depth of this isohaline is generally greater along the coastal regions. This isohaline shallows and reaches the sea surface in the south and central Bay of Bengal.

STABILITY

The vertical distribution of parameters like temperature, salinity, nutrients, etc. is highly dependent on the turbulent diffusion and the vertical component of the field of motion. Vertical mixing depends on the gradient of the flow and the stability of the water column. The stratification of the water column depends on the vertical gradients of temperature and salinity. A stable density gradient suppresses turbulence and hence the transport of sub surface nutrients towards the surface. In an extensive study of the stratification, Rao and Sastry (1981) have observed that the water column of the Bay of Bengal has a higher degree of stratification than in the Arabian Sea. Very high discharge of fresh water into the Bay of Bengal inhibits vertical mixing and so the transfer of nutrients into the euphotic zone.

INTERNAL WAVES

Several studies in the Bay of Bengal reveal high internal wave activity. The strong halocline causes a strong stratification in the water column conducive for internal wave activity. In a climatological sense, the salinity in the Bay is in a quasi steady state, and this implies that considerable amount of salt is transported across the halocline. A possible mechanism of this salt transport is the breaking of the internal waves and this also results in the transfer of nutrients into the surface layers.

DEPTH OF MIXED LAYER

The distribution of wind stress over the northern Indian Ocean and the resulting pattern of near surface circulation are the major factors controlling the depth of the mixed layer. As a result, the intense upwelling off the Somali and Arabian coasts during the SW monsoon period, the thermocline reaches close to the surface and the mixed layer is very

shallow, in spite of the fact that wind stress is maximum during this period (Wyrski 1971). The clockwise gyre which develops off the Somali coast during the SW monsoon is associated with a deep mixed layer (120 m). The large thickness is due to convergence in the clockwise gyre. Off the west coast of India, due to the geostrophic adjustment associated with the southerly current, the thermocline shallows towards the Indian coast. Studies during the International Indian Ocean Expedition have shown a series of clockwise and anticlockwise gyres in the Arabian Sea during the SW monsoon season. Upwelling and consequent rise of nutrient rich water to the euphotic layer in the anticlockwise gyres is expected. The surface circulation, the integral mean concentration of $PO_4\text{-P}$ and the thickness of the mixed layer in the Bay of Bengal are closely related (Rao and Sastry 1981).

DEPTH OF EUPHOTIC LAYER

The depth of the euphotic zone determines the vertical extent of primary production. It is generally taken as that depth where the incident radiation is 1% of that at the sea surface. The spreading of the suspended material brought down by rivers is one of the factors influencing its thickness in the Bay of Bengal. This is clearly shown in charts depicting the depth of euphotic layer (Krey and Babenerd 1976) for June to November. The depth of the euphotic layer may be considered as nearly uniform in other areas of the northern Indian Ocean.

DISTRIBUTION OF NUTRIENTS AND PRIMARY PRODUCTION

NUTRIENTS

The climatic elements help in the redistribution of nutrients especially in the upper 300 metres. The distribution of inorganic phosphate along 10°N and 15°N in the Arabian Sea, has been given by Krey and Babenerd (1976). The effect of upwelling on the distribution of nutrients is clearly indicated by the very high concentration of $PO_4\text{-P}$ off Arabia, Somalia and the south west coast of India. The contours show undulations in the central Arabian Sea during the SW monsoon season coinciding with cyclonic and anti-cyclonic eddies. During the winter season, the concentrations in the regions off Somalia, Arabia and the south west coast of India are generally low as compared to that in the SW monsoon. However, higher values of $PO_4\text{-P}$ at the head of the Bay of Bengal, off Pakistan and in certain zones off Arabia and Gulf of Aden during the NE monsoon period (Fig. 2) are clearly due to upwelling. During the SW monsoon, the higher concentrations seen along the Arabian coasts are also due to upwelling.

CHLOROPHYLL

During the period November to April, the chlorophyll *a* concentrations in the upper 50 metres are high in the north and north eastern regions of the Bay of Bengal, northern regions of Arabian Sea, shelf areas bordering Arabia, Pakistan and the south west coast of India (Krey and Babenerd 1976). The concentration progressively decreases southward. Considering the wind distribution presented earlier, the above areas are favourably situated for upwelling of cold nutrient rich sub surface waters. This process is probably further aided by vertical mixing process in shallow shelf areas.

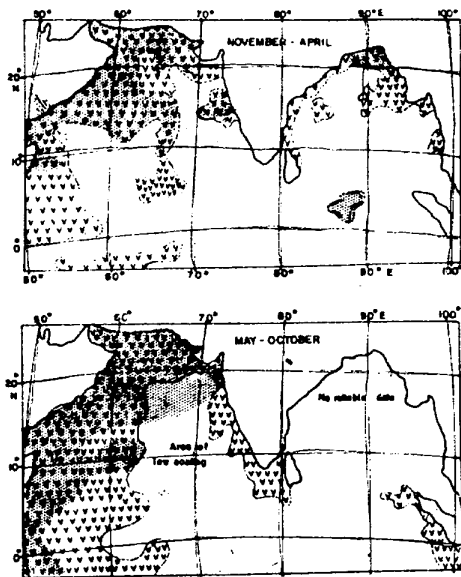


Fig. 2. Areas of high nutrient content and productivity. Shaded Areas : $\text{PO}_4\text{-P}$ concentration at the surface more than $0.3 \mu\text{g l}^{-1}$; vvv Areas : primary production in the euphotic zone more than $250 \text{ mg C m}^{-2} \text{ day}^{-1}$.

The chlorophyll *a* distribution, during the period May to October shows the influence of upwelling and the spreading of upwelled waters off the Somali coast, the Arabian coast and the west coast of India. The chlorophyll *a* values exceed 0.5 mg m^{-3} in the upwelling regions.

PRIMARY PRODUCTION

The integrated mean value of primary production in the euphotic layer (Fig. 2) for the period May to October indicates that the coastal and offshore areas off Somalia, Arabia and the west coast of India have higher productivity. In fact, low productivity rates (less than $100 \text{ mg C m}^{-2} \text{ day}^{-1}$) occur along the 70°E . This region coincides with the region of minimum sea surface temperature decrease (between May and July) as shown by Sastry and Ramesh Babu (1983). It is interesting to note that the regions of minimum SST change and the minimum productivity coincide. Whether it is due to upwelling or mixing due to shear instability, the areas bordering the Arabian Sea are highly productive during the SW monsoon period (also see Qasim 1977 and 1982). In the Bay of Bengal during November to April, the pattern of primary production follows the climatic pattern and the high values are observed at the northern Bay of Bengal progressively decreasing towards south. While similar pattern is seen in the Arabian Sea, a noticeable feature is the low

production observed in the central part of the north Indian Ocean (0-10°N and 70-100°E) during November to April

Thus the studies presented here show that the climate controls the primary productivity of the northern Indian Ocean

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