

## Satellite and ship studies of phytoplankton along the west coast of India

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**Abstract-** Aided by a sequence of chlorophyll images from the Coastal Zone Color Scanner on board the Nimbus-7 satellite and extensive shipboard observations, a descriptive analysis of the factors influencing the distribution and production of phytoplankton along the west coast of India has been presented.

An appreciable degree of spatial and temporal variability was observed, providing adequate evidence of marked seasonality in phytoplankton distribution along the coast.

During the northeast monsoon season, the coastal region south of 20°N was characterized by extremely low chlorophyll associated with the warm, low saline, nutrient impoverished, northwardly flowing equatorial surface waters (ESW). North of approximately 20°N off the coast of Saurashtra, the ESW narrowed to a northwestwardly-flowing jet. In the Gulf of Kutch, intense winter cooling close to the coast led to sinking of newly formed dense water, consequent enhancement of nutrients and high phytoplankton biomass.

During the southwest monsoon, wind-driven upwelling led to nutrient enhancement along the entire coast. However, the response of phytoplankton was evident only during the post monsoon season when irradiance levels were adequate.

### INTRODUCTION

The Arabian Sea is one of the few low-latitude seas under the influence of the monsoons. It is distinct from the others in that it is semi-enclosed and is under the influence of the monsoonal winds which reverse their direction to give rise to two distinct seasons i.e. the northeast monsoon season and the southwest monsoon season. The reversal of the monsoonal winds brings about drastic changes in the large scale circulation patterns (WYRTKI, 1971). In the Central Arabian Sea, BANSE (1984) and BANSE *et al* (1987) have shown that this reversal of winds can induce a marked seasonality in the abundance of phytoplankton in the region, which is far more pronounced than previously recognized.

Along the west coast of India, which forms the eastern boundary of the Arabian Sea, the coastal processes also show a distinct seasonality attributable to monsoonal changes (SHETYE *et al*, 1990; 1991). For example, during the southwest monsoon (June- Sept), the west coast of India experiences upwelling consistent with typical wind-driven eastern boundary upwelling systems. During this period there is a southwardly movement of surface currents and shallowing of isotherms along the coast. Towards the end of the southwest monsoon period, as the onshore component of wind stress recedes, upwelling ceases to be noticeable. With the onset of the northeast monsoon (Nov - March), the surface currents reverse their direction and move northwards all along the coast, carrying warm, low salinity, low nutrient waters from the equatorial region. During this time the isotherms sink on approaching the coast resulting in deepening of the thermocline. In the region north of 15°, this northward flowing current narrows to a jet and turns westwards off the coast of Saurashtra. On either side of the jet, BANSE (1968) and SHETYE *et al* (1991) observed that cold winds blowing from the continent caused considerable heat loss and sinking in the first 50 m or so of the water column.

What are the consequences of this change in the environment on the magnitude and extent of phytoplankton production in this region? This question assumes special significance as the west coast of India supports a sizeable percentage of Indian fisheries. The few studies on the biological productivity of this region have been summarised by QASIM (1977). In the past, one of the major constraints in addressing this issue has been the paucity of shipboard data. This difficulty has now been obviated to a great extent with the National Institute of Oceanography's (Goa, India) ongoing programme "Mapping of living resources in the exclusive economic zone of India" which has provided an opportunity for repeated coverage in this region over space and time.

As seen in the inset in Fig. 1, the monthly averages of shipboard chl *a* data show a distinct seasonal pattern in the distribution of phytoplankton biomass, which appears to be related to seasonal changes in the mixed layer depth. In this figure, chl *a* data from the coast has been segregated into two areas, area 4 and 2 which represent two of the three hydrographic regions demarcated by COLBORN (1975) on the basis of thermal structure. Area 4 is characterised by a permanent shallow thermocline with a bimodal temperature variation and a moderately deep mixed layer during the northeast monsoon. Area 2 is characterised by a permanent shallow thermocline which is also interrupted by a drop in surface temperatures due to upwelling of cool subsurface waters during the southwest monsoon. The southern region of the west coast has been classified separately by COLBORN (1975) as area 11 since this region appeared to be permanently stratified. However recent physical oceanography data from this region suggest that the thermal structure in areas 11 and 2 may not be appreciably different as the effects of upwelling are also felt in area 11 (SHETYE *et al* 1990, 1991 and references cited therein). For the purpose of the present study therefore, area 11 has been grouped along with area 2.

In addition to shipboard data, satellite ocean color imagery from this region has also been used to provide a better idea of the spatial distribution of phytoplankton pigments.

We have also examined the photosynthetic characteristics of phytoplankton under these contrasting environmental conditions. Besides providing an important insight into the factors controlling phytoplankton production (COTE and PLATT, 1984), the parameters describing the photosynthesis versus light curves are now routinely being used in models for predicting production from remotely sensed data (see for example PLATT *et al*, 1988).

## MATERIALS AND METHODS

As has been shown earlier, the most dramatic changes in phytoplankton biomass along the coast are associated with the reversing monsoon periods. Therefore, this study has been limited to these periods. Data from three oceanographic cruises, two during the southwest monsoon (August - September '86 and June - July '87) and one during the northeast monsoon (December - January '88) have been presented. Station positions and the transects covered during the three cruises were almost identical and are shown in Fig.1.

### *Hydrography and water chemistry*

Metallic Nansen Samplers fitted with reversing thermometers were used for temperature measurements and water sampling. Analyses of nutrients and salinity were performed on board using a SKALAR<sup>K</sup> - 6 channel analyzer 5100/1. Salinity was measured with an AUTOSAL<sup>K</sup>, Guideline Salinometer, Model 8400a. Potential density was estimated from the salinity and temperature data.

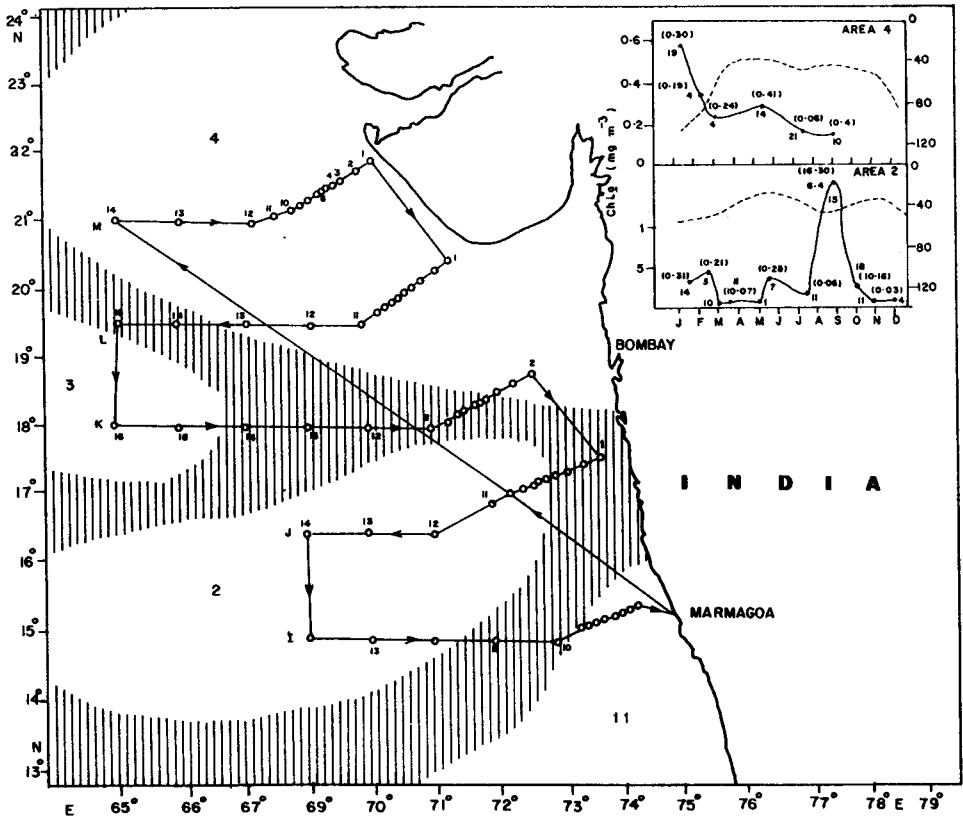


Fig. 1. Station positions with major hydrographic areas defined by Colborn (1975) separated by hatching. Inset shows seasonal distribution of chl *a* in Colborn's (1975) areas 2 and 4 along the west coast of India.

### Biology

Samples for biological analyses were collected with 5-l PVC Niskin samplers from 5 depths corresponding to 100, 60, 30, 16 and 1% of incident irradiance. Light depths were established with a Seechi disc. A Licor Quantum Sensor<sup>R</sup> was used to determine sea surface irradiance. Chlorophyll *a* in water samples filtered onto GF/F filters was determined fluorometrically in 90% acetone extracts using a Turner Designs Fluorometer<sup>R</sup> (STRICKLAND and PARSONS, 1972). Primary production was measured by the <sup>14</sup>C method in 125 ml light and dark bottle samples which were incubated for 24 h on the deck in running sea water (STRICKLAND and PARSONS, 1972). Kahlsico<sup>R</sup> neutral density filters were used to approximate required light intensities. Radiocativity retained in the particulate matter on 0.45 µm polycarbonate filters was measured in a LKB<sup>R</sup> Liquid Scintillation Counter using the channels ratio method for quench correction.

### Satellite data processing

CZCS data collected on board Nimbus-7 was obtained from NASA, USA. Estimates of water-leaving radiances and chl *a* concentrations were obtained after correcting for sensor degradation and atmospheric effects using the algorithms of GORDON (1978), GORDON and CLARKE (1981) and GORDON *et al* (1983).

## RESULTS AND DISCUSSION

The discussion on shipboard observations for the two seasons is restricted to two transects, the northern one located at  $20^{\circ}\text{N}$  and the southern transect located at  $15^{\circ}\text{N}$ . Both transects were oriented more or less perpendicular to the coast and were selected as they come under the regions classified as areas 4 and 2 (Fig. 1).

### *Northeast monsoon*

#### *Transect $15^{\circ}\text{N}$*

Vertical distributions of temperature, salinity and density along transect  $15^{\circ}\text{N}$  shown in Figs. 2a, b and c respectively, indicate strong vertical stratification of the water column. The temperature and salinity distribution along this section show the presence of a low-salinity, warm-water pool roughly 400 km wide and extending to a depth of 75 m. This pool marks the northward flowing ESW.

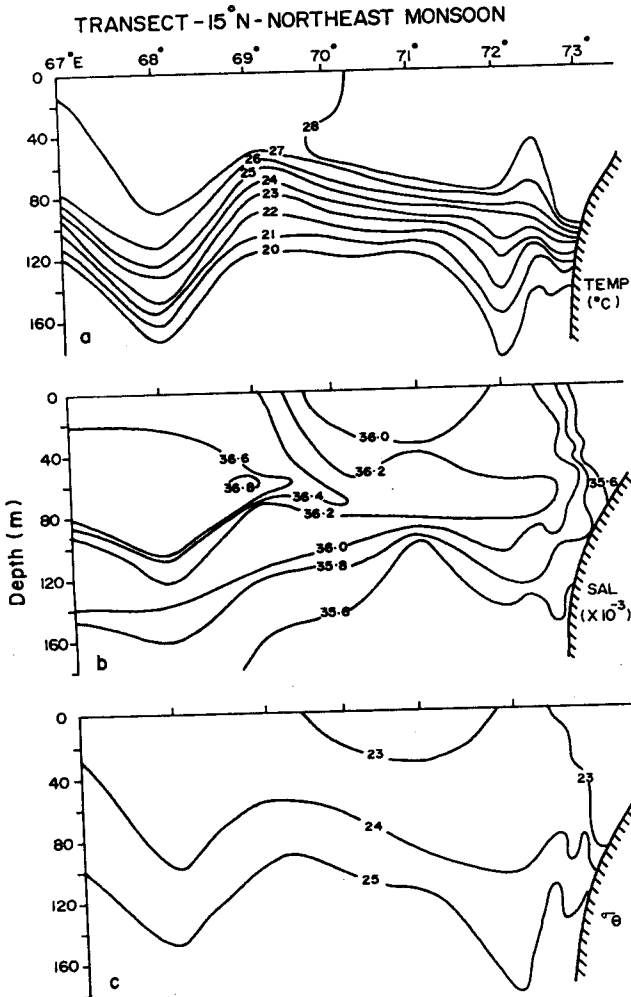


Fig. 2. Vertical section of a) temperature b) salinity and c) density along transect  $15^{\circ}$  during the northeast monsoon.

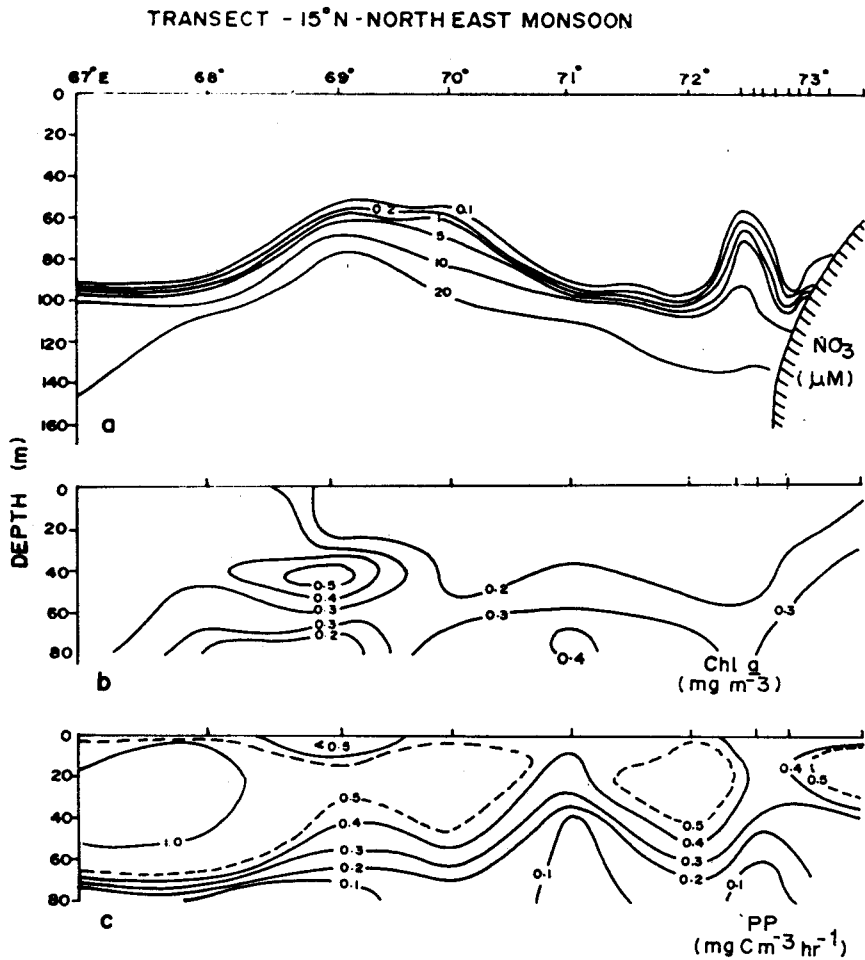


Fig. 3. Vertical section of a) nitrate b) chl *a* and c) primary production along transect 15° during the northeast monsoon.

Nitrate in the euphotic zone was undetectable both offshore and near the coast, confirming the stratified nature of the water column. The nitracline was located between 80 to 90 m (Fig. 3a).

Low chl *a* values ranging between 0.1 to 0.57 mg m<sup>-3</sup> characterised the entire transect (Fig. 3b). The differences between chl *a* values observed at nearshore and offshore stations were marginal. Primary productivity values were also low and ranged from 0.03 to 1.15 mgCm<sup>-3</sup>h<sup>-1</sup> (Fig. 3c).

#### *Transect 20° N*

A northward decrease in water column temperature was evident along the 20° N transect (Fig. 4a). The waters in the coastal region were vertically homogeneous. Temperature in the entire column was around 26.2 °C, much cooler than that observed in the waters offshore. Immediately off the shelf, the isotherms dipped sharply by as much as 75 m over a very short distance, suggesting rapid downwelling in this region.

BANSE (1968) attributed the formation of cool waters along the shelf to cold, dry winds blowing from the continent. On account of the shallow depth of this region, cooling was highly efficient. Salinity in this region was also low probably due to river run-off (Fig. 4b). The waters close to the shelf were much denser (Fig. 4c) and indicated an apparent tendency to cascade below the warmer water away from the shelf. Off the shelf break, signatures of the ESW were observed in the top 60 m over a distance of approximately 75 km indicating the northward flow of these water. Offshore winter convection led to deepening of the mixed layer to around 60 m.

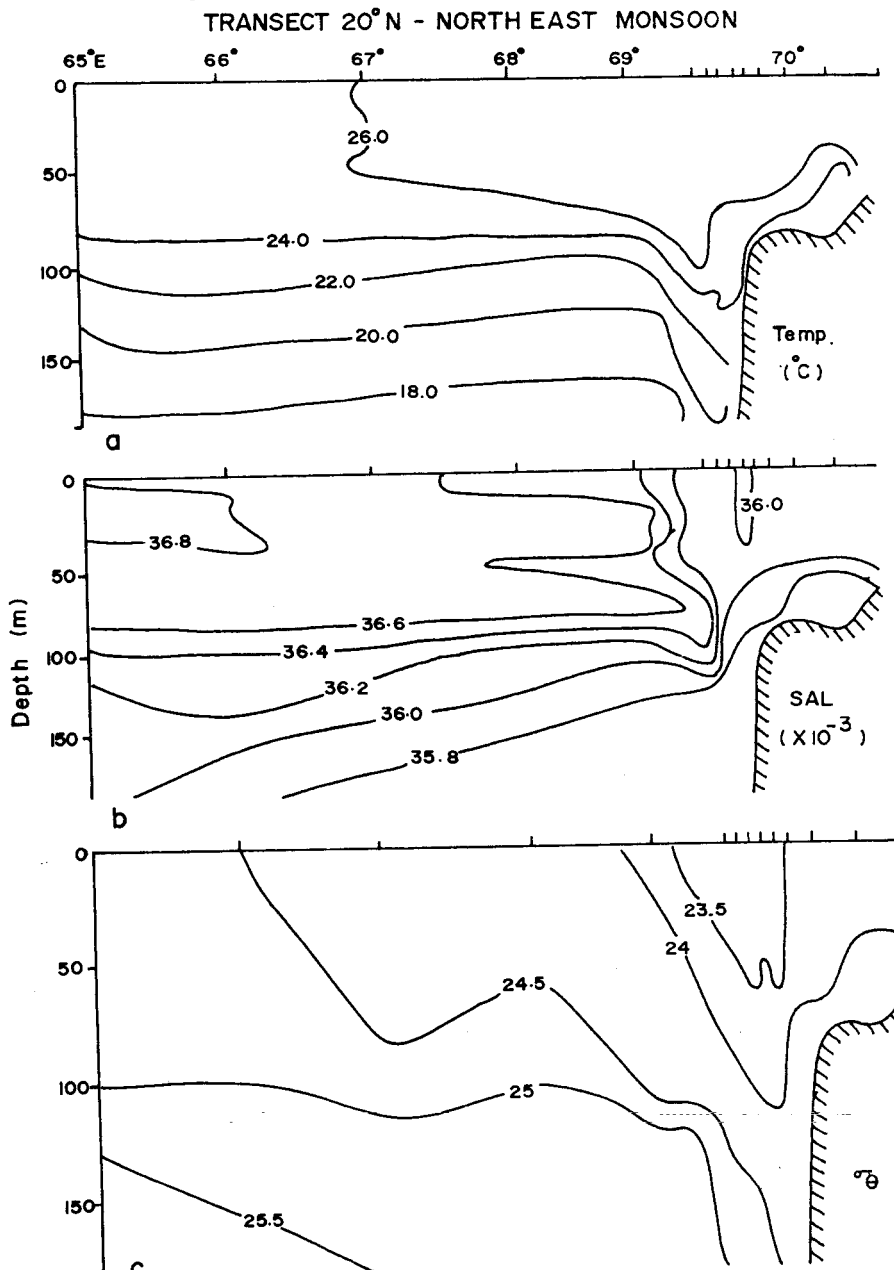


Fig. 4. Vertical section of a) temperature b) salinity and c) density along transect 20°N during the northeast monsoon.

Nitrate values varied between undetectable to 0.05  $\mu\text{mol}$  in the euphotic column (Fig. 5a). The nitracline was located around 80 m. Chlorophyll *a* concentrations ranged from 0.6 to 1.61  $\text{mg m}^{-3}$  and were highest in the region adjacent to the continental margin, where winter cooling was observed (Fig. 5b). Within a narrow strip of about 50 km off the shelf break region in the core of the warm ESW, chl *a* concentrations were less than 0.5  $\text{mg m}^{-3}$ . Further offshore, chl *a* showed an increase. The concentrations were however, almost half those observed near the continental margin. Primary productivity varied between 0.08 to 3.12  $\text{mg C m}^{-3} \text{h}^{-1}$  and closely resembled the distribution pattern observed for chl *a* where the highest values were recorded in the coastal region (Fig. 5c).

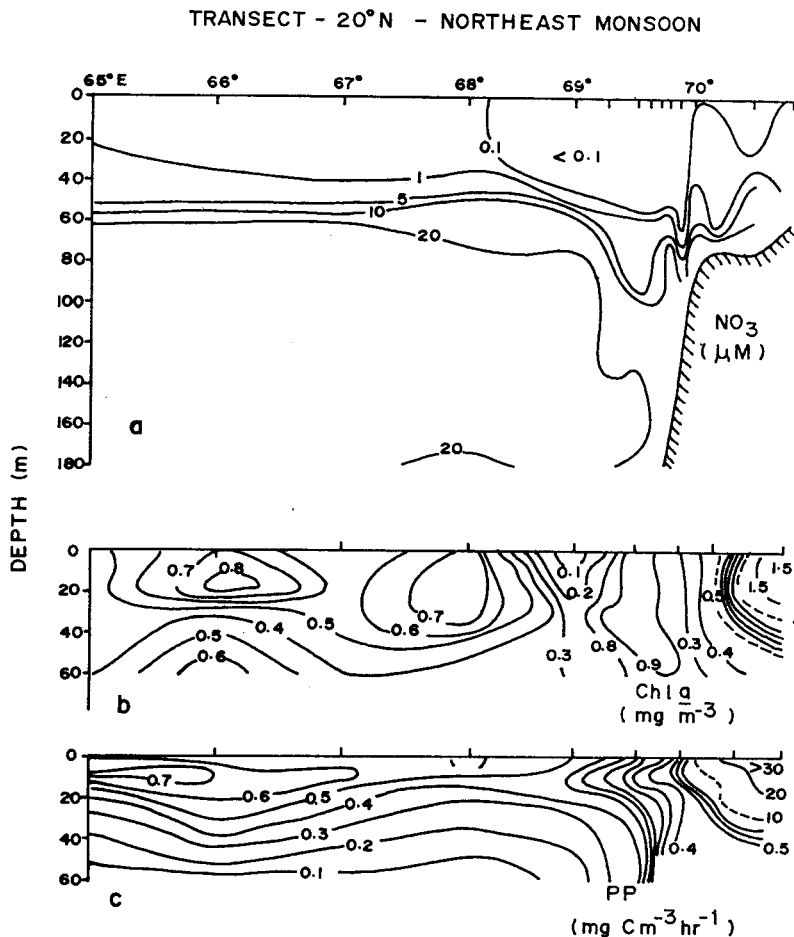


Fig. 5. Vertical section of a) nitrate b) chl *a* and c) primary production along transect 20° N during the northeast monsoon.

### Satellite image

The CZCS scene for January 1979 clearly highlights the consequence of surface circulation on the distribution of phytoplankton (Trace 1). The northward flowing ESW carrying low salinity, warm waters leads to strong stratification all along the coast which is reflected in the extremely low chlorophyll values observed. The northern extent of this

region of stratification is limited by the thermal front which is oriented at almost right angles to the coast of Saurashtra (20°N). In this region, the ESW narrows to a jet less than 60 km wide in agreement with the observations of SHETYE *et al* (in press). Chl *a* concentrations within the core of the jet are seen to be markedly low. The inshore region of the front also marks the southern limit of the region of winter convection where the chl *a* values observed are much higher than those south of the front. The pattern of chl *a* distribution also validates the earlier observation of SHETYE *et al* (in press) that winter convection is not as efficient along the offshore side of the front as compared to the inshore region.

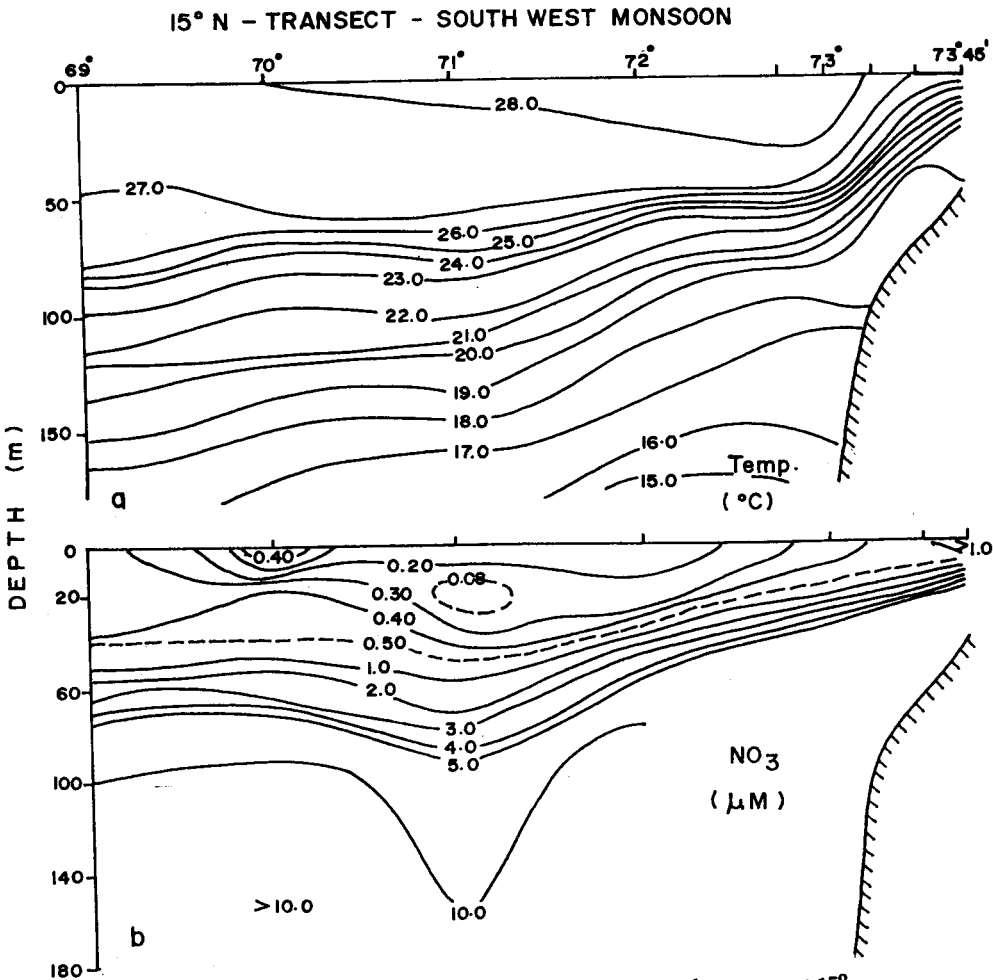


Fig. 6. Vertical section of a) temperature and b) nitrate along transect 15° during the southwest monsoon.

### Southwest monsoon

#### Transect 15°N

Along this transect, the isotherms showed a sharp tilt towards the coast. The mixed-layer depth varied from 90 m offshore to around 20 m near the coast (Fig. 6a). The upslope of isotherms, together with the fact that the longshore component of wind



15° N - TRANSECT - SOUTH WEST MONSOON

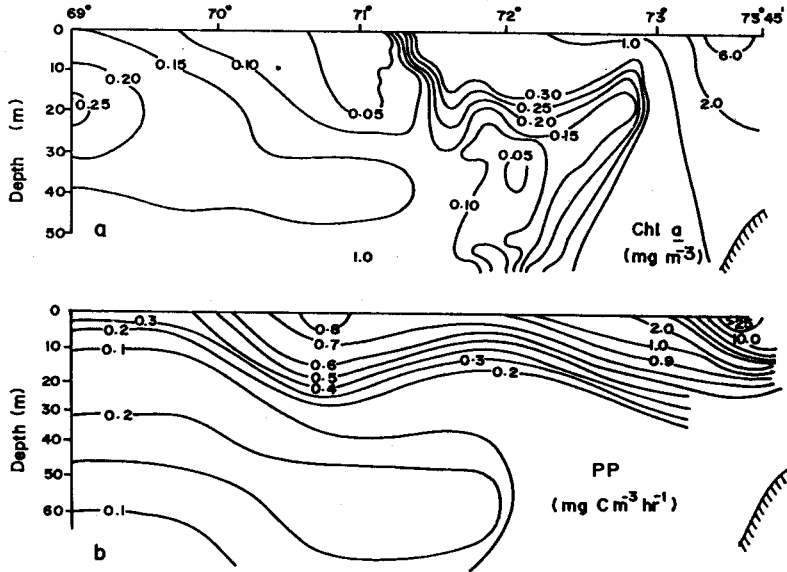


Fig. 7. Vertical section of a) chl *a* and b) primary production along transect 15° during the southwest monsoon.

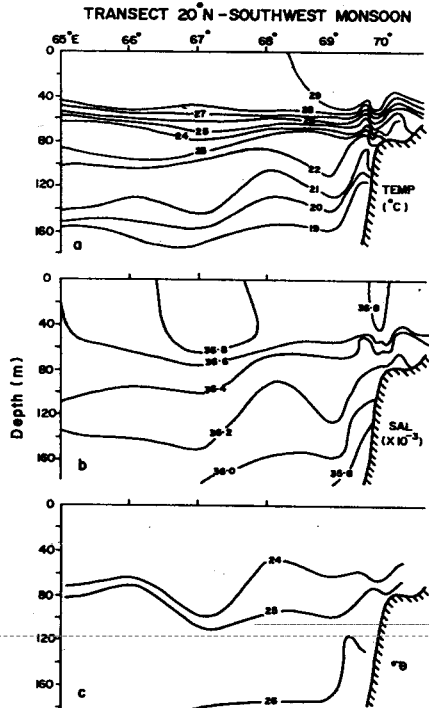


Fig. 8. Vertical section of a) temperature b) salinity and c) density along transect 20°N during the southwest monsoon.

stress was equatorward, indicated that this region was experiencing upwelling. On the basis of a favourable comparison between annual cycles of the longshore component of wind stress and ship-drift along this coast, SHETYE and SHENOI (1988) concluded that local winds drive surface circulation during the southwest monsoon. A favourable comparison was also seen between the annual cycle of the longshore component of wind stress and the mean thermal structure on the shelf, implying that winds control upwelling in this region (SHETYE *et al*, 1985).

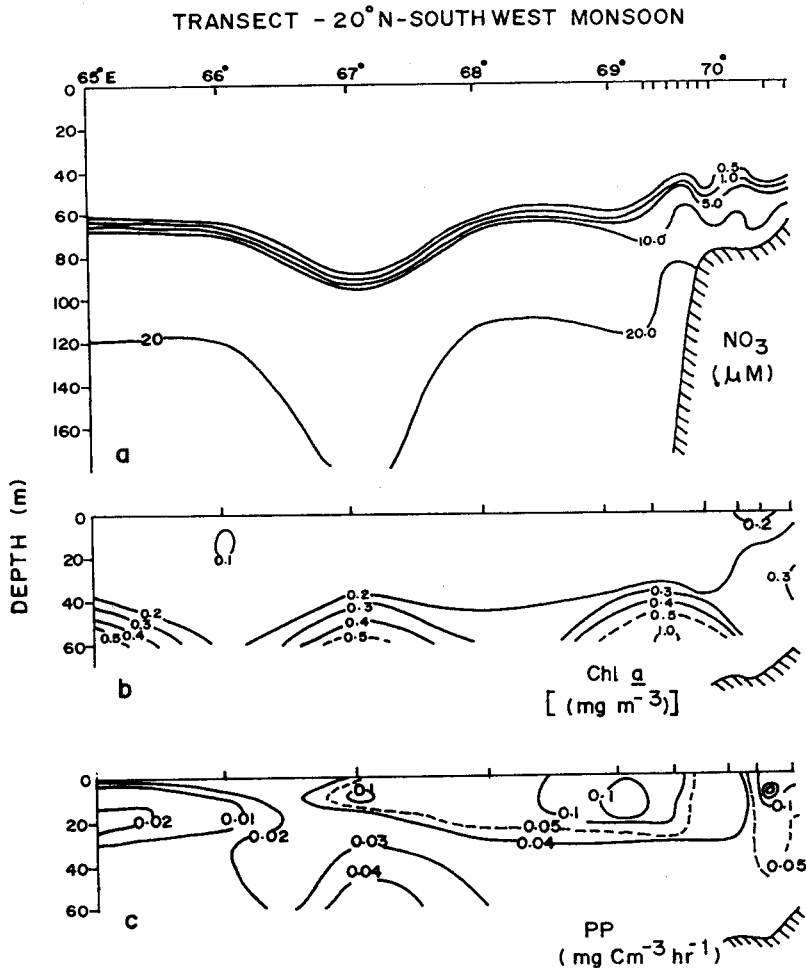


Fig. 9. Vertical section of a) nitrate b) chl *a* and c) primary production along transect 20°N during the southwest monsoon.

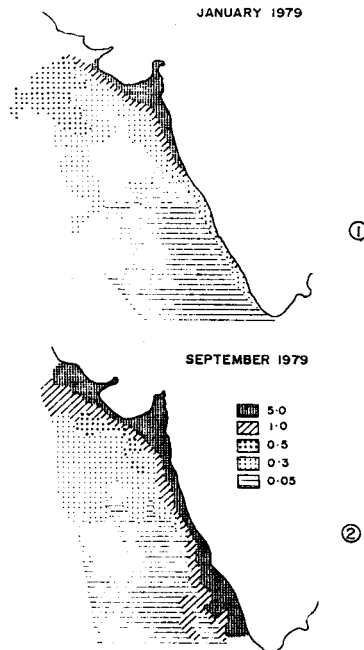
Nitrate values were quite high in the zone of upwelling but were undetectable in the region offshore (Fig. 6b).

Chlorophyll *a* values offshore were uniformly low (between 0.05 and 0.25 mg m<sup>-3</sup>), but showed a dramatic increase to around 2.0 mg m<sup>-3</sup> towards the zone of upwelling (Fig. 7a). In the core of the upwelling zone, chl *a* values peaked to 6.0 mg m<sup>-3</sup>. As in

the case of chl *a*, primary productivity also showed a marked difference between stations in the offshore stratified region and those in the core of the upwelling zone (Fig. 7b). The values offshore were  $1.0 \text{ mg C m}^{-3} \text{ h}^{-1}$  and around  $29 \text{ mg C m}^{-3} \text{ h}^{-1}$  in the region of upwelling.

#### Transect 20°N

The waters on this northern transect were much warmer as compared to the southern transect. No signatures of upwelling were noticeable in the sections of temperature, salinity and density (Figs. 8a, b and c).



Trace 1. Chlorophyll *a* ( $\text{mg m}^{-3}$ ) distribution drawn from CZCS imagery along the west coast of India during the month of January. Trace 2. Chlorophyll *a* ( $\text{mg m}^{-3}$ ) distribution drawn from CZCS imagery along the west coast of India during the month of September.

Nitrate values confirmed the strong vertical stratification of these waters (Fig. 9a). SHETYE *et al* (1990) observed that upwelling was generally not noticeable north of 15°N. The disappearance of the upwelling signatures in this region was attributed to the decline in the longshore component of wind stress.

On account of the stratified nature of the waters along this transect, chl *a* values were extremely low ( $0.1 - 0.2 \text{ mg m}^{-3}$ ) in the upper euphotic waters (Fig. 9b). A deep chl *a* maximum was observed at around 60 m corresponding to 1% of the surface light intensity. Primary productivity values were also extremely low ( $0.005 - 0.27 \text{ mg C m}^{-3} \text{ h}^{-1}$ ) along the entire transect (Fig. 9c).

#### Satellite image

Due to persistent cloud cover during the southwest monsoon, we have not been able to obtain an appropriate scene for the monsoon months. Since the effects of upwelling

were seen to persist till late October (GOMES *et al*, present symposium paper), we have presented a scene for the month of October 1979 (Trace 2) to represent this period. This scene provides ample evidence of the marked seasonal differences in phytoplankton abundance, especially pronounced near the the coast between the southeast and northeast monsoon periods. The distribution of chl *a* in this scene also shows the declining intensity of upwelling northwards. The patchy distribution of chl *a* all along the south and central west coast also appears to suggest that upwelling along the coast is controlled by local winds in agreement with the findings of SHETYE *et al* (1985) and SHETYE *et al* (1990).

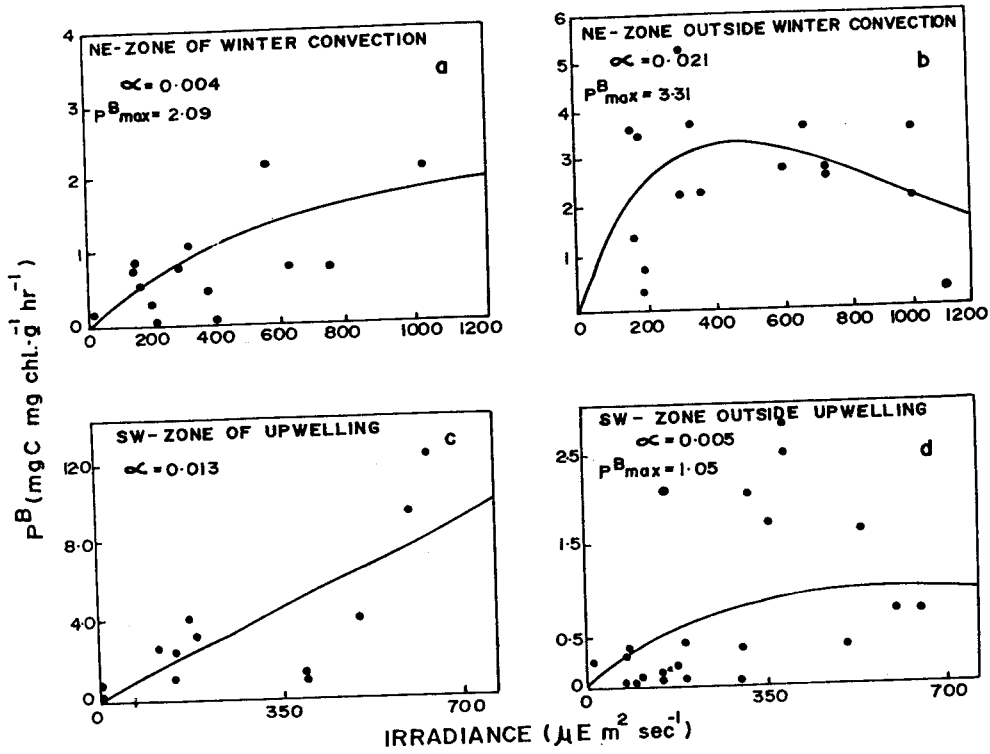


Fig. 10. Chlorophyll *a* normalised photosynthesis versus light curves for phytoplankton from different regions and seasons.

**Photosynthetic characteristics of phytoplankton:**

A comparison of the photosynthetic characteristics of phytoplankton from within and outside the zones of winter convection and upwelling during the northeast and southwest monsoon are depicted in Fig. 10. Photosynthetic rates normalised to unit chl *a* were plotted against irradiance and parameters describing these curves were obtained by fitting to pooled sets of data from different seasons, the equation of PLATT *et al* (1986). The initial slope of the light saturation curve ( $\alpha$ ) ( $mg C m^{-3} h^{-1}$ ) ( $mg chl a$ )<sup>-1</sup> ( $\mu E m^{-2} sec^{-1}$ ) which is related to the efficiency of photosynthesis at low light intensities, indicated that phytoplankton from outside the zone of winter convection much more efficient at low light intensities ( $\alpha = 0.021$ ) as compared to those from within the zone of winter convection ( $\alpha = 0.004$ ). The parameter characterising chl *a* specific photosynthesis at light saturation ( $P^B_{max}$ ) was also higher in phytoplankton outside the zone of of winter convection where nitrate was undetectable. COTE and PLATT (1984) showed that parameters of the

photosynthesis versus light curves could provide interesting insight into the interaction of phytoplankton with their environment. PLATT *et al* (1986) observed that the parameters of the photosynthesis versus light curves were influenced to a great extent by nutrient availability. The decline in photosynthetic rates for samples from outside the zone of winter cooling probably reflects nitrate limitation. A comparison of the photosynthetic characteristics of phytoplankton during the southwest monsoon revealed that phytoplankton from within the nutrient-rich upwelled waters were more efficient at low light intensity ( $\alpha=0.013$ ) than those in the stratified water column outside the zone of upwelling ( $\alpha=0.005$ ), which suggests that the former benefits from the abundant nutrients in the water column. It was also noted that, in general phytoplankton populations were more shade adapted during the southwest monsoon than during the northeast monsoon.

## CONCLUSIONS

During the northeast monsoon, a large area along the west coast of India outside the region of winter convection is covered by equatorial surface waters. In the offshore region, these waters are characterised by a permanent discontinuity layer that prevents effective fertilization of the euphotic column. Rates of primary production in this region therefore, remain at a low level throughout the year. Nitrate availability appears to be the major factor limiting phytoplankton photosynthesis and depends to a large extent on the rate and intensity of vertical diffusion across the pycnocline. In most instances, nitrate concentrations in the euphotic zone were much below the half saturation constants reported for their uptake by oceanic phytoplankton (MAC ISAAC and DUGDALE, 1969; EPPLEY *et al* 1979). The only measurements of vertical eddy diffusion in the Arabian Sea have been made by WAFAR *et al* (1986) which suggest that nutrient recycling in the euphotic zone is relatively unimportant. However, these measurements were confined to a single cruise and may not be representative of different seasons and regions.

The onset of the southwest monsoon causes a substantial increase in production. The production during the upwelling period was much higher than that observed during winter cooling. Higher export production or flux of organic particles out of the euphotic zone may therefore be expected during the southwest monsoon as compared to the northeast in agreement with the findings of NAIR *et al* (1989). Winter convection close to the coast in the northern region and upwelling along the southwest coast are two important mechanisms that lead to enhanced production. Interestingly both these processes are influenced by the magnitude and direction of the prevailing winds. Another aspect of interest not considered in the present study is the occurrence of the nitrogen-fixing algae *Trichodesmium* which are known to contribute substantially to the overall production before the onset of the southwest monsoon period when strong thermal stratification results in low nutrient concentrations in the water column (DEVASSY *et al* 1978).

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