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Hydrological structure and biological productivity of the tropical Indian Ocean

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Abstract

Hydrological structure analyses of regions in the tropical Atlantic Ocean have consistently revealed the existence of a typical tropical structure characterized by a nitrate-depleted mixed layer above the thermocline. The important biological significance of the top of the nitracline in such situations has been established. The primary production and chlorophyll maxima coincide with the top of the nitracline, this being the level at which conditions for primary production are optimum in terms of light and nutrients. The existence of a similar structure has also been reported in the tropical Pacific.

The present study addresses the possibilities of the existence of a 'typical tropical structure' in the Indian Ocean, taking into account the monsoonal conditions that are unique to this region. While wind forcing and evaporation dominate the Arabian Sea dynamics, the Bay of Bengal is largely influenced by freshwater runoff and precipitation, in addition to the wind effects. In view of their different oceanographic conditions, these two distinct regions of the northern Indian Ocean have been treated separately in the analysis of data (historical as well as those from the JGOFS (India) cruises). The study focuses on the regional as well as seasonal variations in the oceanographic parameters and nutrient distribution, with an attempt to relate to biological productivity.

1. Introduction

In the tropical Atlantic Ocean, Herbland and Voituriez (1979) have identified a typical tropical structure (TTS) of the ecosystem in the euphotic layer. Their analysis facilitated an approximation of the integrated phytoplankton biomass and production in the water column from any vertical profile of nitrate, nitrite, *in vivo* fluorescence, oxygen and temperature. This was possible as the depths of the nitracline, oxycline and chlorophyll maximum were found to be statistically the same in the TTS. Besides, when vertical advection was negligible there was a relationship between the depth of the nitracline and the depth of the maximal thermal gradient. The universal nature of such relationships for tropical waters has, however, not been established as data, especially for *in situ* primary production, are scanty.

Unlike the Pacific and the Atlantic, the Indian Ocean experiences unique climatic conditions which give rise to the monsoons. The two basins of the northern Indian Ocean, namely, the Arabian Sea and the Bay of Bengal, have different oceanographic conditions. While wind forcing and evaporation dominate Arabian Sea dynamics, the Bay of Bengal is largely influenced by fresh water runoff and precipitation in addition to the wind effects. From June to September (SW monsoon) winds at the west coast of India favor upwelling with strong southward alongshore drift and the subsurface countercurrent seems to be hugging the entire west coast (Shetye et al., 1990). During the NE monsoon period (December - March) the current reverses and flows against the weak northerly wind as a result of themo-haline forcing (Shetye et al., 1984). The advection of highly saline Arabian Sea water mass from the north appears to prevent the cool subsurface water from reaching the surface close to the coast, especially at northern latitudes (Muraleedharan and Prasannakumar, 1996). The winter cooling mechanism (Prasannakumar and Prasad, 1996) and the proximity of the Findlater Jet (Bauer et al. 1991) keep the northern Arabian Sea productive throughout the year while advection from the Somali coast enriches the central Arabian Sea (Prasannakumar et al., 1999). East coast upwelling is not as prominent as that at the west coast due to several reasons. Remote forcing is believed to be one of the causes which suppresses the upwelling mechanism along the east coast in the Bay of Bengal (Sengupta, personal communication).

This study is an attempt to understand whether or not a TTS exists in the tropical Indian Ocean. In view of the above complexities it was considered imperative to focus on the regional as well as seasonal variations in the parameters, while attempting an analysis of the hydrological structure in the tropical Indian Ocean.

2. Data and Methodology

The study was primarily based on the data from five cruises undertaken on board ORV *Sagar Kanya* as part

Table 1. Details of the cruises of ORV *Sagar Kanya* (SK) and R.V. *Gaveshani* (GV) selected for the present study.

Seasons	Months	Cruises	
		Arabian Sea	Bay of Bengal
NE monsoon	Dec. - Feb.	SK 121, SK99, Sk37, GV 145	GV 164, GV 128
Inter-monsoon	Mar.- May, Sep. - Oct.	SK 91	SK 41
SW monsoon	Jun. - Aug.	SK 115, SK 104, SK 34, SK 33	SK 53

of the Arabian Sea JGOFS (Joint Global Ocean Flux Studies) programme: SK 91 (April-May 1994), SK 99 (Feb - Mar 1995), SK 104 (July-Aug 1995), SK 115 (July-Aug 1996), and SK 121 (Feb 1997). All sampling and analysis techniques followed for this data collection were as per the JGOFS International Protocol.

The above data set (1994 to 1996 period) was supplemented by data from selected earlier cruises by the National Institute of Oceanography, Goa (spanning 1983 to 1989, data documented at INODC, NIO, Goa). These data helped to confirm that the results of the attempted analysis reflected true and permanent features of the tropical Indian Ocean and ensure that contributions due to interannual variability may be smoothened out. On the whole, data collected during 14 cruises onboard RV *Gaveshani* and ORV *Sagar Kanya* were chosen as summarized in Table 1.

Only such physical/chemical/biological data were chosen where it could be ascertained that the techniques used for their collection best conformed to standard protocols.

All data were analyzed separately for the Arabian Sea and the Bay of Bengal and discussed with respect to three seasons : NW monsoon, SW monsoon and the Transition (intermonsoon) periods.

3. Results and Discussion

The variations of the maximal thermal gradient with respect to the depth of the thermocline (i.e., depth of the maximal thermal gradient) over the tropical Indian Ocean are depicted in Fig. 1. In this aspect there were no observable differences between the Arabian Sea and the Bay of Bengal but it was interesting to note that high thermal gradients (maximum of 0.9°C m^{-1}) were recorded during the SW monsoon period in contrast to the distinctly lower gradients (maximum of 0.4°C m^{-1}) during the NE monsoon. Likewise, the thermocline lay above 120 m during the SW monsoon but deepened to almost 190 m during winter. The summer monsoon period was thus characterized by higher thermal gradients and comparatively shallower thermoclines. In this season there was also a trend of the maximal thermal gradient increasing with the deepening of the mixed layer (Fig. 2). During the NE monsoon, however, although

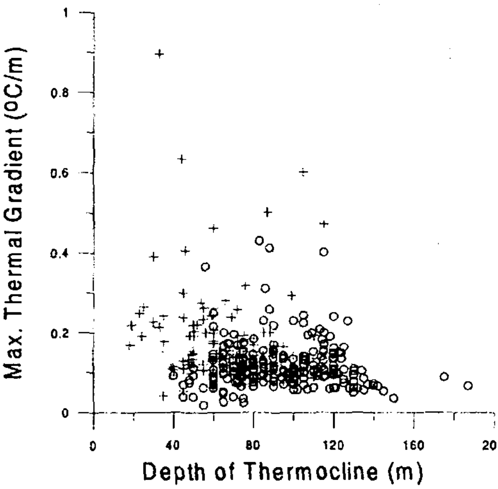

Fig. 1. Variation of the maximal thermal gradient with depth of the thermocline during the south-west (+) and north-east (o) monsoon seasons in the tropical Indian Ocean (n=398).

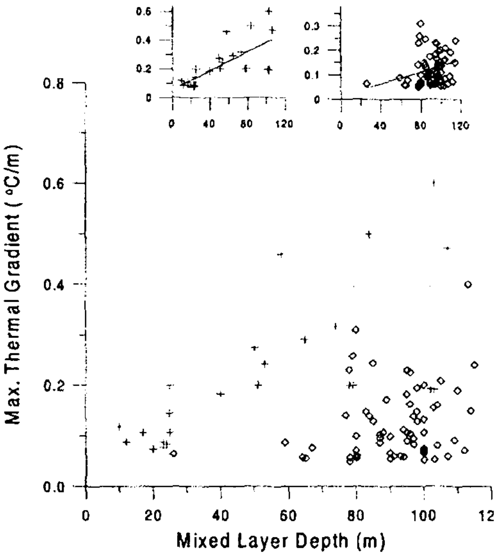

Fig. 2. Relationship between the maximal thermal gradient and the mixed layer depth (n=93) during the southwest (+) and northeast (□) monsoon seasons in the Arabian Sea. The insets show the regression lines for the individual seasons.

the mixed layer was consistently deeper than 60 m, no relationship with the maximal thermal gradient could be identified. It is worth noting that the abnormally deep, weak thermocline (>120 m) is observed at the northern Arabian Sea during winter (Fig. 1). During this season the northeastern Arabian Sea is under the influence of a unique air-sea interaction process – the winter cooling mechanism (Prasannakumar and Prasad, 1996), which produces intense vertical mixing capable of penetrating the subsurface stability barrier. This would give rise to a very deep mixed layer overlying a weak thermocline. The cluster of data points observed during the northeast monsoon (Fig. 2) is a manifestation of this peculiar situation.

Fig. 3 shows an inverse relation of the mixed layer depth (MLD) with the sea surface temperature (SST). In general, shallow mixed layers were associated with warmer surface waters, a fact which was specifically evident during the intermonsoon (transition) periods where SST was often in the range of 28° to 30.5°C. It is understandable that in the Arabian Sea where surface temperatures of 24°C were extremely common in winter, they never fell below 26°C in summer. Surface warming makes the layer more stable and the momentum transfer from atmosphere to ocean is less significant giving rise to the degradation of the mixed layer. On the contrary, surface cooling destabilises the surface layer leading to sinking and convective mixing, a process that supports building up of the MLD. It is, therefore, not unrealistic to state that the SST more or less acts as a surface expression of MLD (Fig. 3).

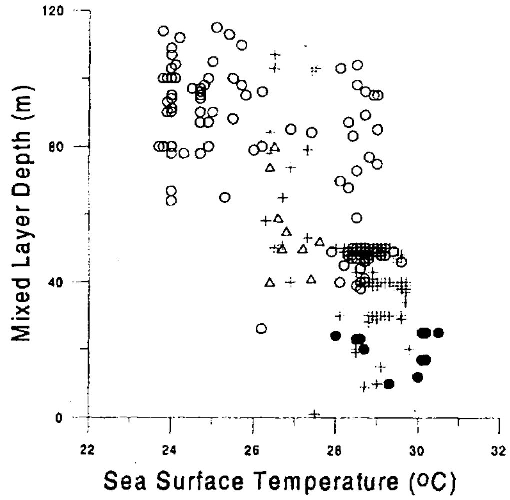

Fig 3. Relationship between the mixed layer depth and sea surface temperature (n=253) during the northeast (o), southwest (+) and intermonsoon (•) seasons in the Arabian Sea and during the northeast monsoon in the Bay of Bengal (Δ).

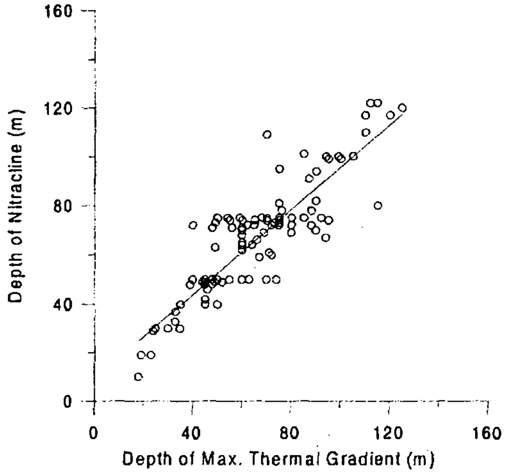

Fig. 4. Linear regression between the depth of the nitracline and the depth of thermocline (n=127) in the southwest and the intermonsoon seasons in the Arabian Sea.

The Bay of Bengal was distinct in that its surface waters during the winter monsoon were always at 26° to 27.5° C and MLDs rarely deeper than 75 m.

Herbland & Voituriez (1979) have analyzed the relationship between the depth of the nitracline (DNO_3) and the depth of the maximal thermal gradient (D_{GTmax}) in the tropical Atlantic Ocean and reported the equation of linear regression as

$$DNO_3 = 0.77\, D_{GTmax} + 11.2.$$

They inferred that when D_{GTmax} was less than 49 m the level of the nitracline was statistically below the level of the maximal thermal gradient and that beyond 49 m nitrate crossed the barrier of stability. Our data for the summer monsoon and transition periods in the Arabian Sea (Fig. 4) compared favourably with the above, following the linear regression equation

$$D\,NO_3 \;=\; 0.87\, D\,GT_{max} + 9.2$$

with a significant coefficient of correlation of $r = 0.87$. In this case, the threshold depth of the maximal gradient for which nitrate crossed the stability barrier was calculated to be 71 m. For the same seasons in the Bay of Bengal no correlation of significance could be obtained (data not shown). This could be attributed in part to the scarcity of data over this region of the tropical Indian Ocean.

Through all seasons and for all regions of the tropical Indian Ocean considered in this study, the top of the nitracline practically coincided with the first level of undersaturation in oxygen (Fig. 5) , the linear regression equation being

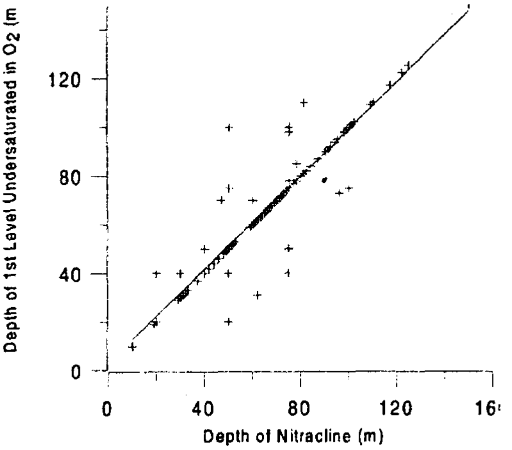

Fig. 5. Linear regression between the depth of the first level of undersaturation in oxygen and the depth of the nitracline for all seasons in the tropical Indian Ocean (n=394)

$$D\,O_2 = 0.96\,D\,NO_3 + 3.3 \qquad (r = 0.96).$$

Such a spatial coincidence between the depths of the oxycline and the nitracline was also recorded from the tropical Atlantic Ocean (Herbland & Voituriez, 1979). In the same report, the authors had also observed that the primary nitrite maximum was located about ten to twelve metres below the top of the nitracline and that this level defined the bottom of the euphotic layer where light limits primary production. As the depth of the chlorophyll maximum was statistically the same as the top of the nitrate gradient, such a 'typical tropical' situation could rationalize an earlier proposal (Voituriez and Herbland, 1977b) wherein nitrite (an indicator of nitrate uptake) was suggested as an indicator of "new production". In our studies in the tropical Indian Ocean, we obtained the relationship

$$D\,NO_2 = 0.86\,D\,NO_3 + 7.0 \qquad (r = 0.84)$$

between the depth of the primary nitrite maximum (DNO_2) and the top of the nitracline (Fig. 6). This would imply that in this tropical region, the primary nitrite maximum was almost coincident with the top of the nitrate gradient and rarely deeper.

In typical tropical situations of the Atlantic Ocean, within certain limits, the chlorophyll maximum and the primary production maximum were observed to follow the nitracline. In such cases it was possible to estimate the integrated value of chlorophyll and primary production by means of the depths of the nitracline, oxycline or chlorophyll maximum which are statistically the same (Herbland and Vorturiez, 1977a,1979). While in our studies, the inter-relationships between the thermocline, maximal thermal gradient, nitracline, oxycline and the primary nitrite maximum appeared to follow a 'TTS' at least for certain seasons/regions of the tropical Indian Ocean, correlations with biological productivity were not as conclusive (data not shown). This could be attributed to several factors, notable among which are – (1) the inconsistencies in the conventional methods of productivity measurements coupled with the variability of data from source to source and (2) the too large depth intervals used for the routine sampling, which often lead to a missing of the real maxima. Nevertheless, we have observed a general linear relationship between the depth of the chlorophyll maximum ($D\,Chl_{max}$) and $D\,NO_3$ (Fig. 7) given by

$$D\,Chl_{max} = 0.54\,D\,NO_3 + 12.6.$$

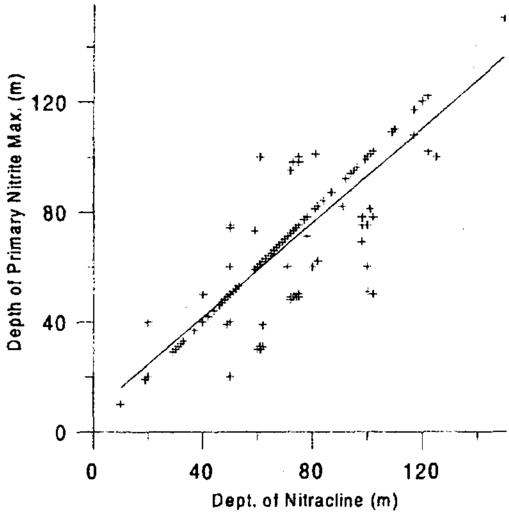

Fig. 6. Linear regression between the depth of the primary nitrite maximum and the depth of the nitracline for all seasons in the tropical Indian Ocean (n=371).

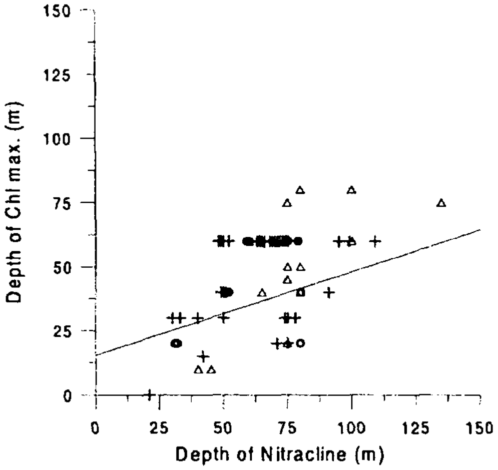

Fig. 7. Linear regression between the depth of the chlorophyll maximum and the depth of the nitracline (n=78) for the southwest (+), northeast (o) and intermonsoon(•) seasons in the Arabian Sea and for the intermonsoon period in the Bay of Bengal (Δ).

Despite the rather low correlation coefficient of 0.56, this study has given cause for hope that with the availability of more consistent data on chlorophyll and primary production, it may be possible to arrive at meaningful relationships between the physico-chemical and biological parameters for the distinct seasons and regions of the tropical Indian Ocean. In addition to the possibility of predicting productivity from more easily and accurately available parameters ,as was found possible in the tropical Atlantic (Voituriez and Herbland, 1981), studies of such inter-relationships would also prove interesting in view of the more recent reports on the biological modulation of SST (Nakamoto et, al., 2000; Sathyendranath et al.,1991).

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