Seasonal variability in oxygen and nutrients in the central and eastern Arabian Sea

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Extensive observations made in the central and eastern Arabian Sea under JGOFS (India) programme suggest strong seasonal variations in concentrations of oxygen and nutrients in the water column. In the intermediate waters (depth range 150–800 m) oxygen concentrations were lowest during winter (with values near zero at ~400 m) in relation to those in the other two seasons (intermonsoon and southwest monsoon). This together with nitrate distributions revealed the occurrence of intense reducing conditions in intermediate waters during winter because of the sluggish water movement and high surface productivity. Secondary nitrite, an indicator of occurrence of denitrification was present at oxygen levels < 10 μM. Nitrate deficits reached a maximum of 10 μM in winter, whereas, it was half this value in monsoon. The average deficits suggest increasing reducing conditions in the order monsoon (1.6 μM), intermonsoon (3.7 μM) and winter (4.0 μM).

THE Indian Ocean experiences seasonally variable surface circulation. During the southwest monsoon, upwelling occurs along the east coasts of north Africa and Arabia[1,2] and the southwest coast of India[3,4]. This results in high biological production, making the Arabian Sea one of the most productive areas in the world oceans[5]. High biological production and subsequent sinking of organic matter leads to high oxygen demand in intermediate waters. Although the renewal of intermediate waters is quite rapid[1,6], this high demand leads to the development of intense oxygen minimum at intermediate depths where oxidized nitrogen species are reduced to molecular nitrogen[6–11]. Denitrification in the Arabian Sea is estimated to be about 1/3 of the global ocean denitrification[6] which has been shown to vary between northeast (winter) and southwest (summer) monsoon seasons with higher nitrate deficits during the former[12]. In this article we report the seasonal variability in reducing conditions in intermediate waters and the influence of physical processes, such as upwelling and winter convection, on the property distributions using the data collected as a part of the JGOFS (India) programme.

Data sets used were collected in the central and eastern Arabian Sea water column during the ORV *Sagar Kanya* cruises SK-91 (April–May), SK-99 (February–March) and SK-104 (July–August) representing the intermonsoon, winter and southwest monsoon periods, respectively. During the SW monsoon, samples could be collected only up to 18° N. Figure 1 shows the cruise tracks. Water samples were collected using a Seabird CTD rosette, fitted with 12 Niskin bottles of 1.8/12/30 litre capacity. Dissolved oxygen was measured by Winkler titration during SK-91, and by spectrophotometric method[13] during SK-99 and SK-104. The spectrophotometric measurement of oxygen improved the precision significantly, particularly at low oxygen levels (at 4 μM it is ± 0.1 μM). The analyses of nitrite, nitrate and silicate were done using a Skalar Analyser 5100/1. Phosphate was measured spectrophotometrically using the method of Murphy and Riley[14].

The distribution of oxygen in the upper 1000 m during the three seasons is shown in Figure 2. The data show the lowest oxygen concentrations in winter. Its minimum reached near-zero levels during this season while in monsoon it was ~15 μM. The distribution of nitrate during the three sampling periods is shown in Figure 3. The surface waters were devoid of nitrate during the intermonsoon period. In winter nitrate was about 2 μM in the surface waters of northern latitudes result-

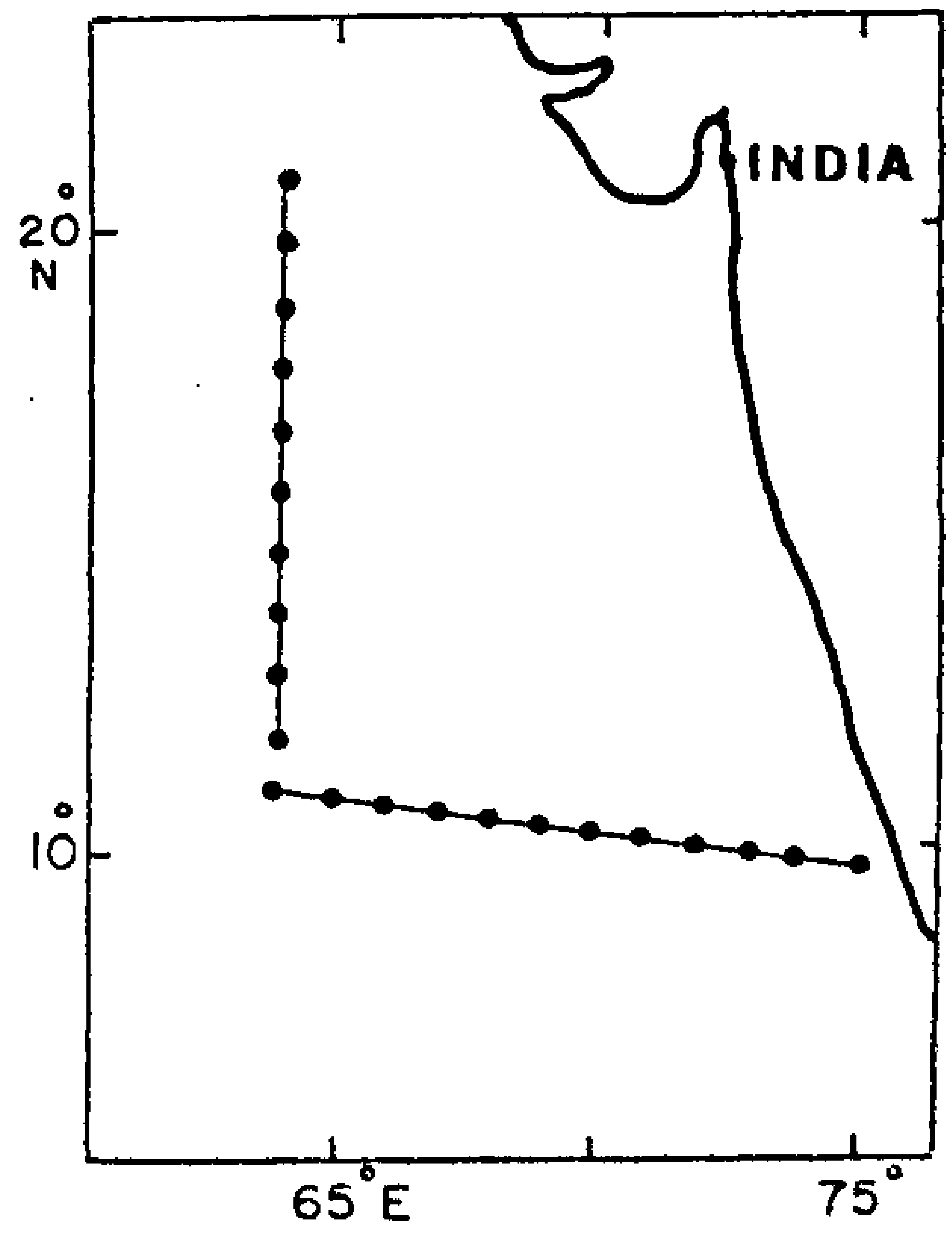

Figure 1. Map showing cruise tracks.

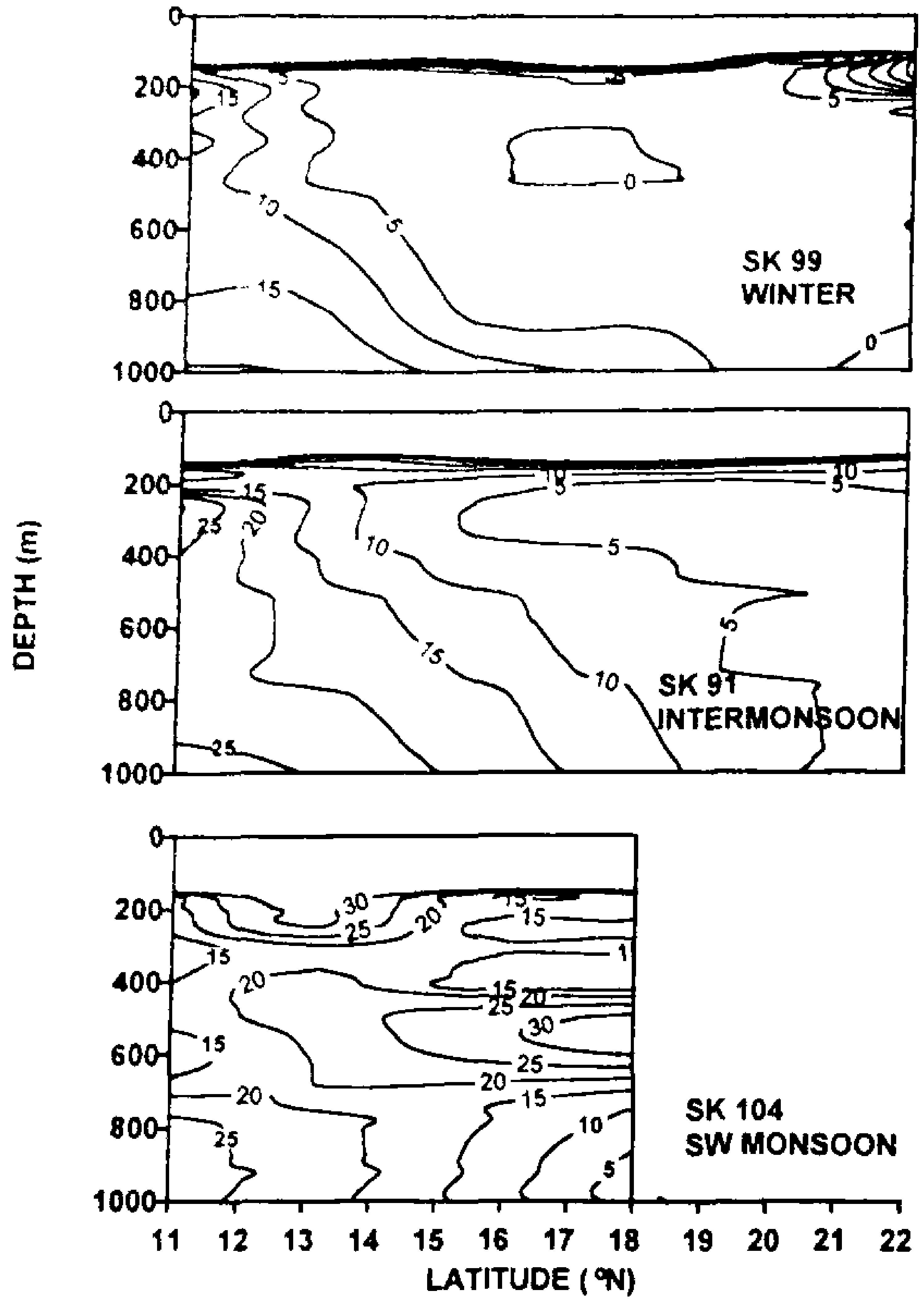

Figure 2. North–south variations in dissolved oxygen (μM) along 64°E; contours shown for levels < 30 μM only.

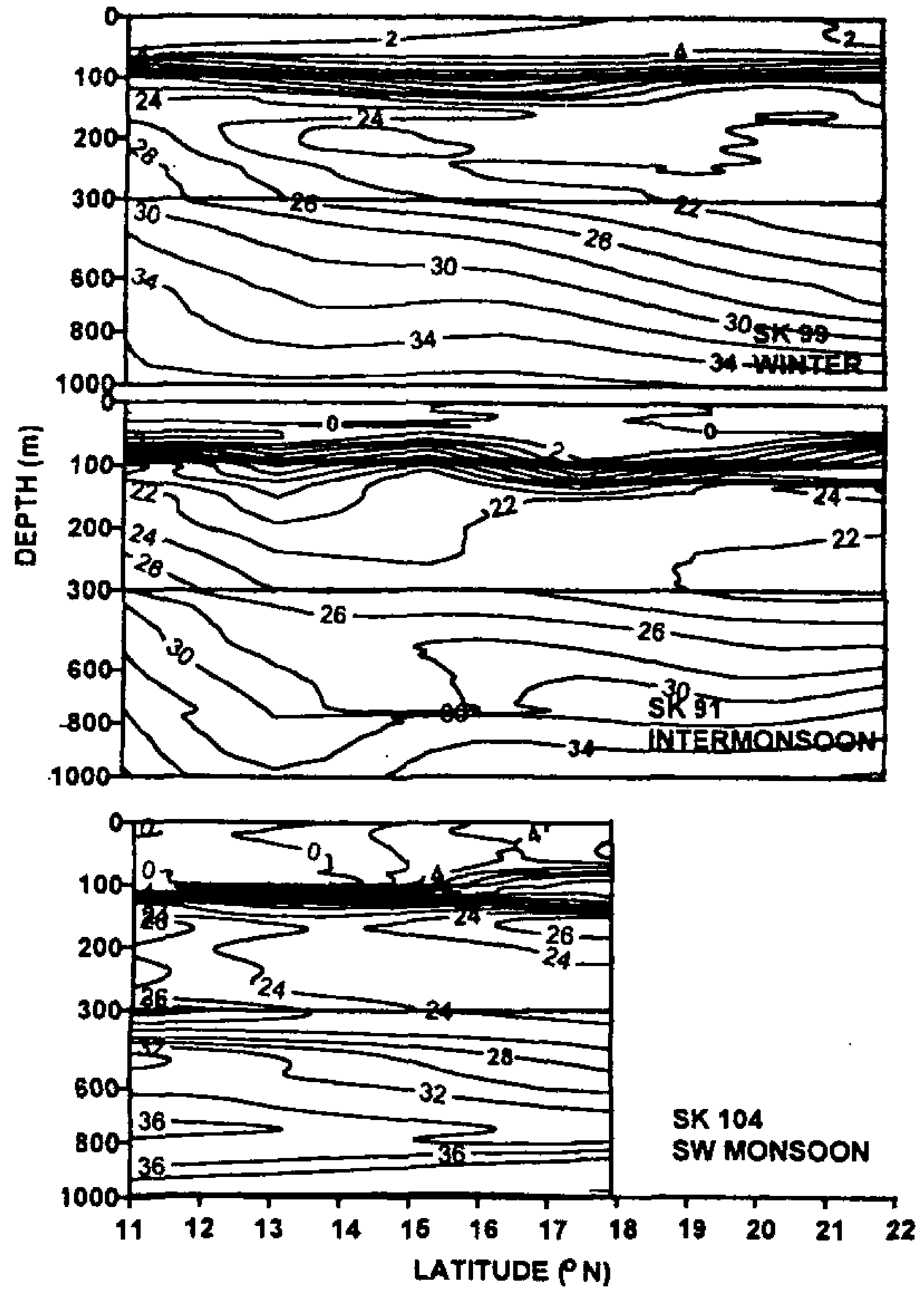

Figure 3. North–south variations in nitrate (μM) along 64° E.

ing from wintercooling and convective mixing[15,16]. These data are consistent with primary productivity measurements during these two seasons[16,17]. In monsoon there is a conspicuous high nitrate patch in surface waters at about 16° N (Figure 3). This patch is also characterized by lower temperature and higher oxygen concentrations, signatures of upwelling, resulting from gyral circulation[18] or wind regime of Findlater jet[19]. The depth profiles of nitrate in general show that, at any given depth the concentrations were lower in the northern latitudes. This probably results from the consumption of nitrate in these regions for combustion of organic matter. Due to enhanced surface productivity in winter, the large amounts of organic matter should be oxidized in intermediate layers, thus leading to oxygen-deficient conditions. When the oxygen is present at trace levels, the bacteria utilize nitrate as oxidant for the decomposition of organic material. During this process nitrate gets reduced to elemental nitrogen as the end product with nitrite as an important intermediate. Thus the presence of nitrite below the thermocline indicates the occurrence and the intensity of denitrification process.

Figure 4 is a plot of nitrite and oxygen in monsoon and winter observed in samples from surface to 1000 m. The data show that there are two distinct ranges of oxygen levels in winter where nitrite was present. One is near the upper thermocline region with oxygen concentrations of 175–275 μM and the other is in intermediate depths with oxygen <10 μM. Such distinction could not be made for monsoon since the oxygen in subsurface layers is also relatively high. While nitrite present in sub-oxic waters indicates the occurrence of denitrification, that in the thermocline region originates from nitrification process[7]. Data for monsoon (inset) suggest that secondary nitrite can occur in the presence of trace levels (5–10 μM) of oxygen. However, the oxygen has been reduced further during winter mainly because of its enhanced consumption triggered by the rain of organic matter from surface layers.

The estimated nitrate deficit[7] (DELN), a measure of nitrate decrease due to its reduction to molecular nitrogen, ranged from 0 to 10 μM in the waters between 100 and 1000 m. The highest DELN values were found in winter, particularly in the north (Figure 5) with clearly discernible north–south gradients. In the intermonsoon period, the high DELN values were found at ~14° N because of relatively low nitrate pocket observed at ~200 m. In monsoon, in spite of the relatively high oxygen in intermediate waters, DELN reached a value of ~5 µM. This indicates that the Arabian Sea experiences denitrification in all the seasons but its extent is variable. This is obvious from Figure 6 which shows

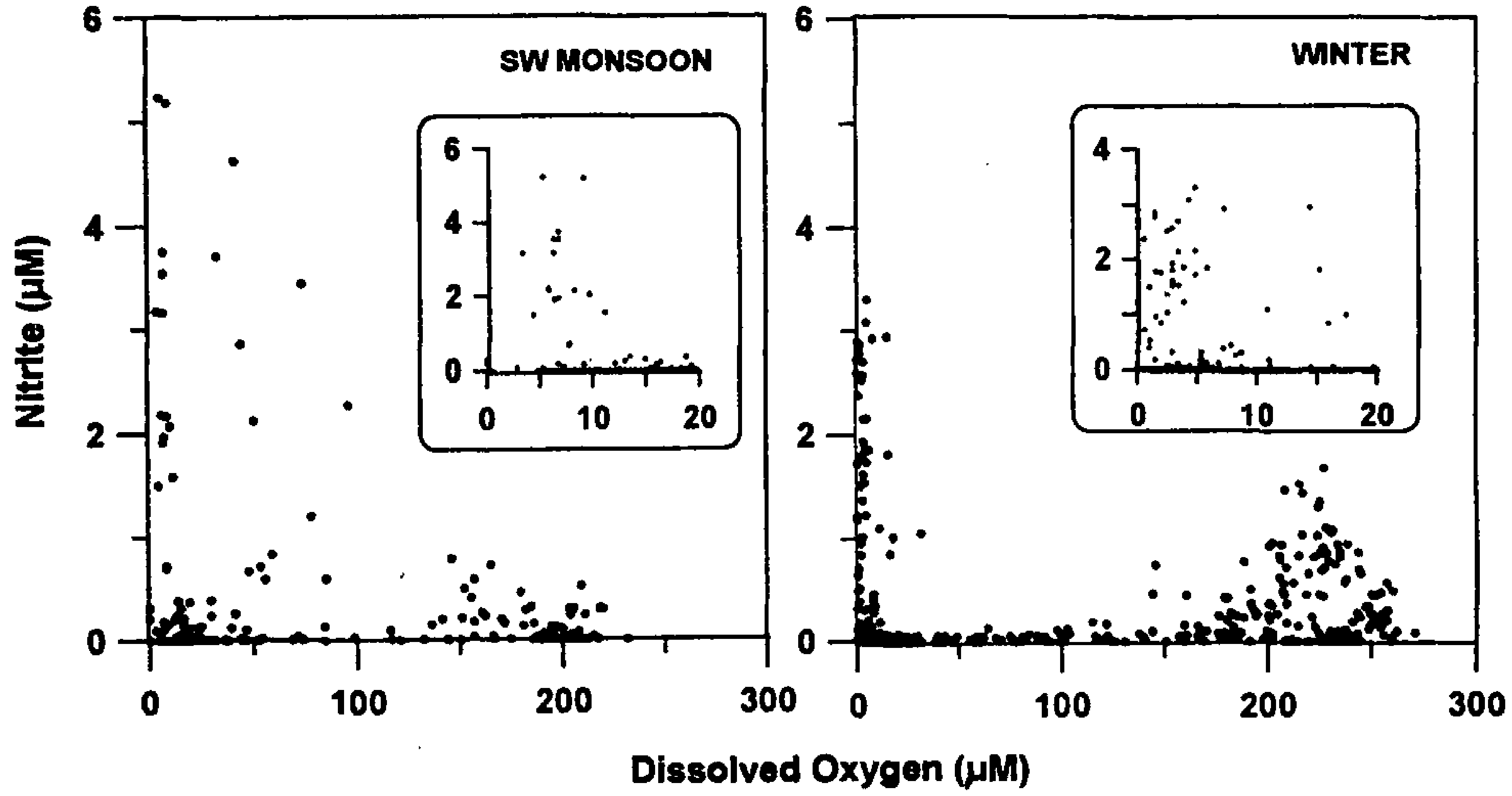

Figure 4. Relation between dissolved oxygen (µM) and nitrite (µM) during monsoon and winter.

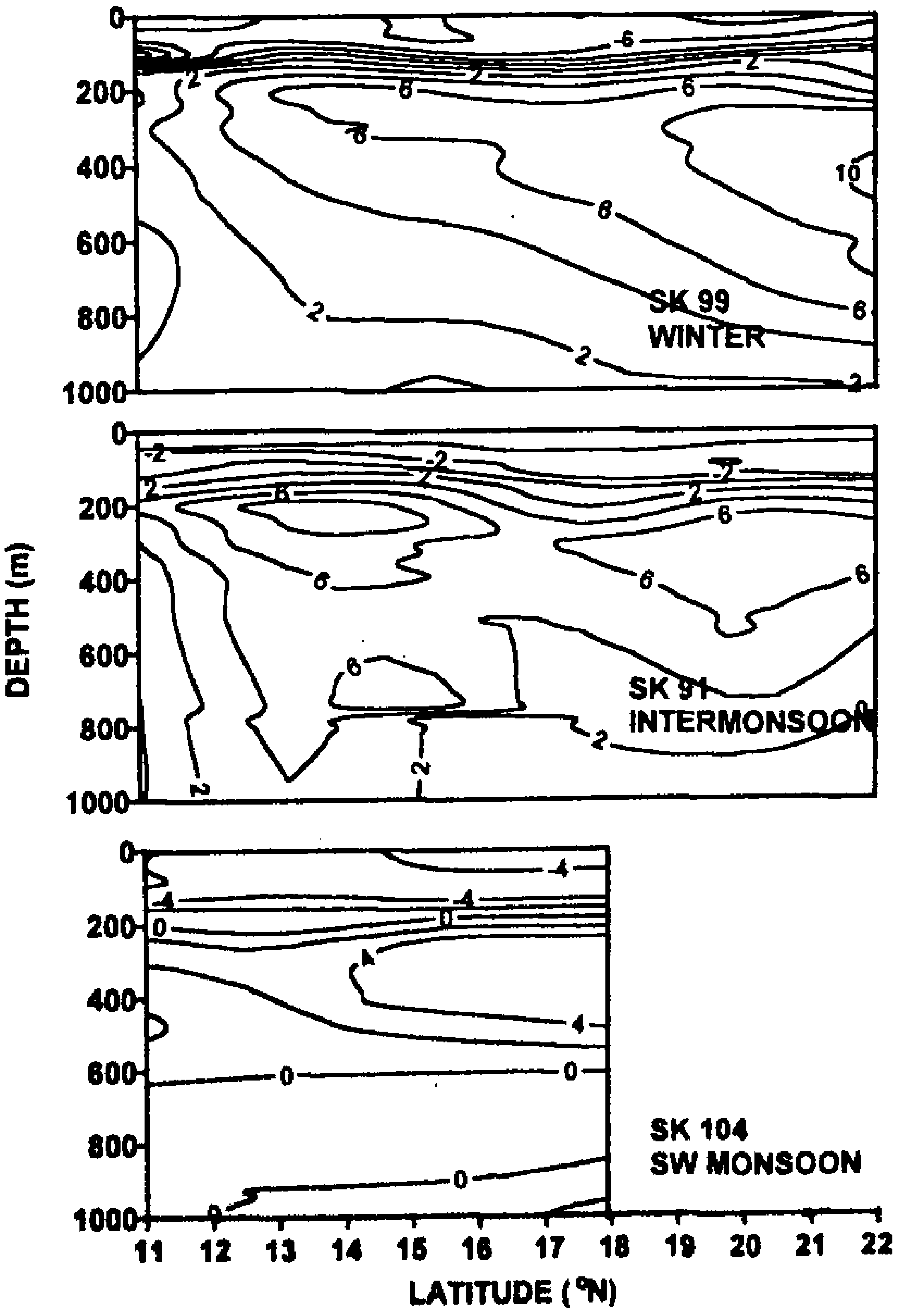

Figure 5. North–south variations in nitrate deficit (DELN, µM), along 64°E.

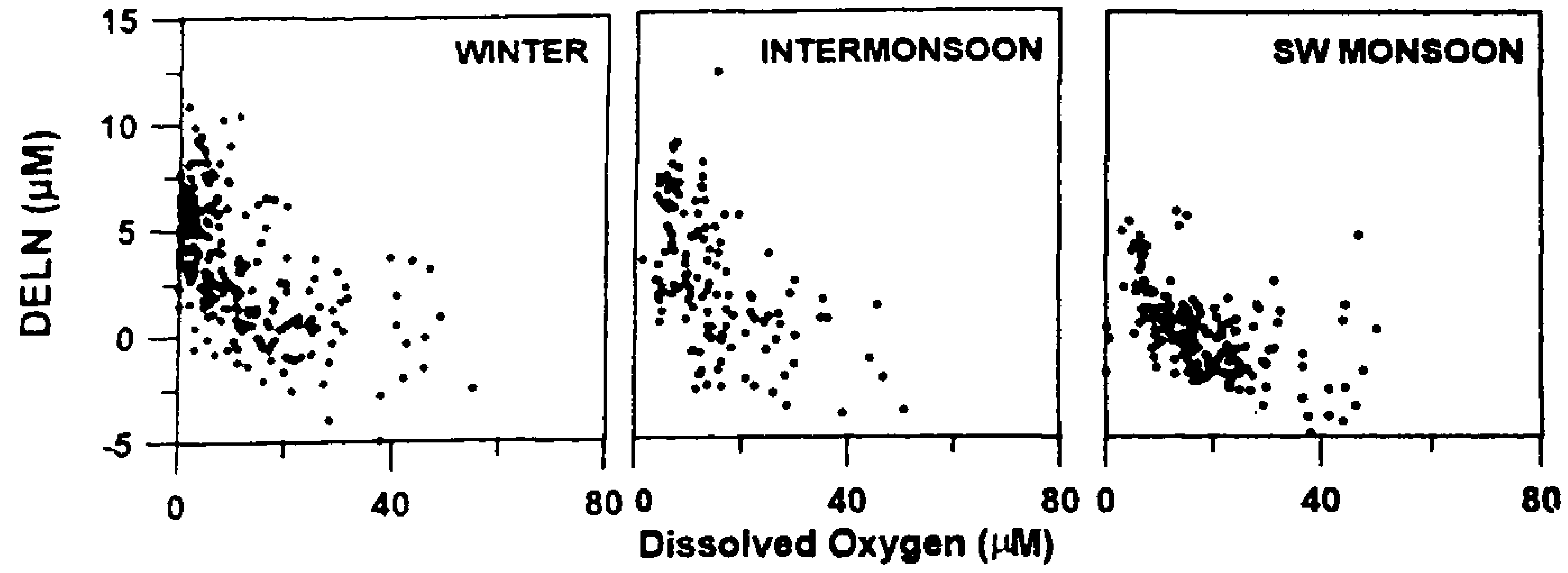

Figure 6. Dissolved oxygen (at <60 µM) versus DELN (µM) during different seasons along 64°E.

the relationship between dissolved oxygen and DELN; for O_2 concentration ≤60 µM for different seasons. A large number of points have positive DELN values in winter particularly below 10 µM of oxygen. This is in good agreement with that of nitrite (Figure 4).

During winter, convective mixing facilitates the upward pumping of nutrients-laden subsurface layers[15,16]. Figure 3 shows the influence of this winter mixing on nutrient pumping; the nitrate isoline of 2 µM surfaced in the northern latitudes. This process is more vigorous in the northeastern region of the Arabian Sea where the mixed layer deepens to ~100 m, leading to relatively higher biological production. For instance, in winter[17] the primary production was 807 mgC m^{-2} d^{-1} at 21°N and 67°E while it was 335 mgC m^{-2} d^{-1} at 11°N and 64°E about a factor or two higher than that during the intermonsoon season; 310 and 163 mgC m^{-2} d^{-1} at these stations, respectively[17]. Hence, the observed variations in nitrate (Figure 3) and total carbon dioxide[20] abundances are in agreement with the gradients in productivity. The high surface primary production[17] together with the sluggish renewal of intermediate waters[1,12] could have resulted in the intense reducing conditions in winter (Figure 5).

Intense upwelling occurs in the northwestern Arabian Sea but of moderate intensity along the southwest coast of India[4,21,22]. In addition to that shown in Figure 3, Figure 7 depicts the signatures of upwelling in the eastern side of the east–west section in Figure 1. This occurred to the east of 72°E where the surface temperatures were less than 28°C. The effect could also be

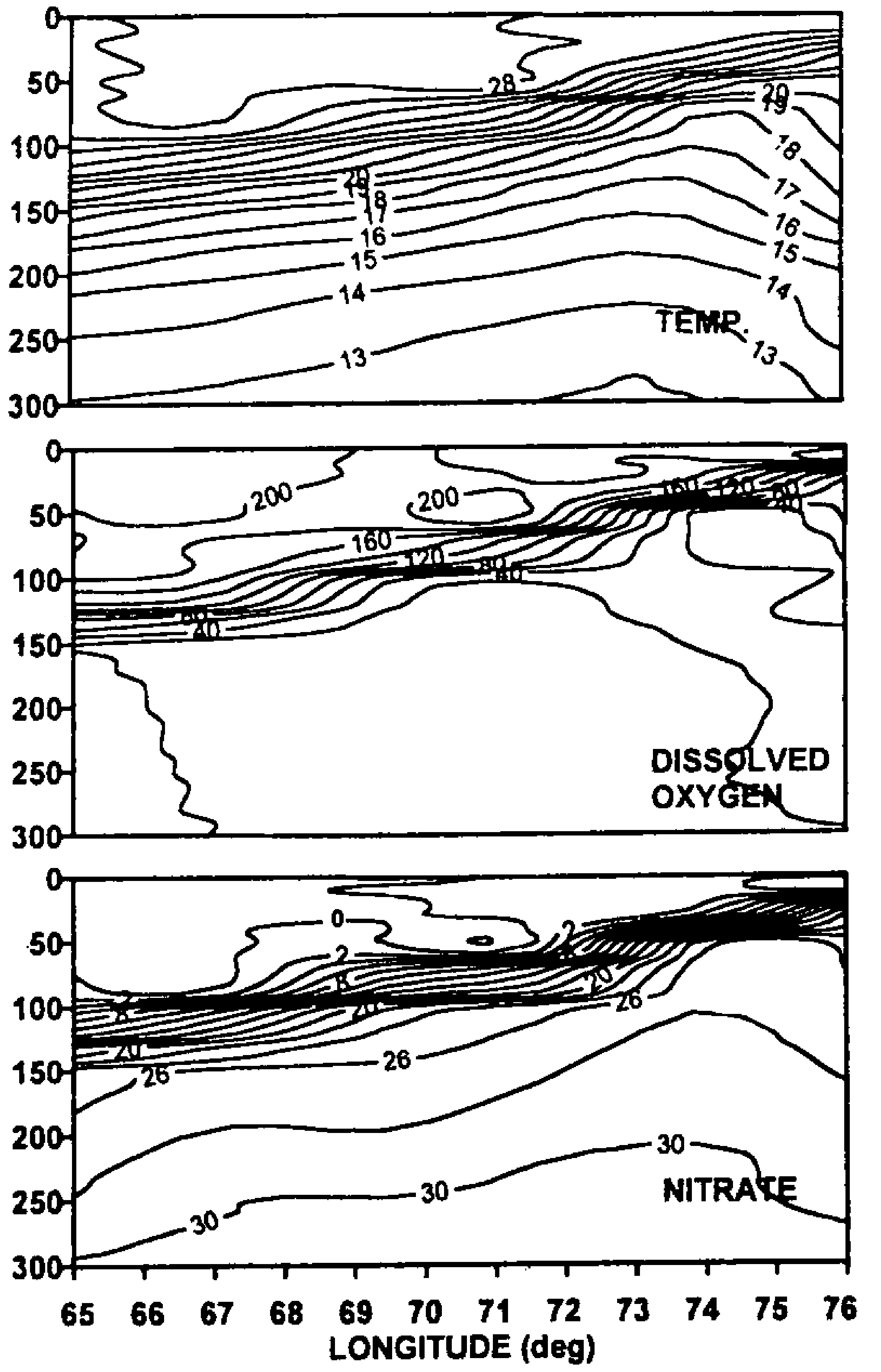

Figure 7. East-west distribution of temperature (°C), oxygen (µM) and nitrate (µM) during SW monsoon.

Table 1. Average values of oxygen and nitrate deficit (DELN) in denitrification zone and surface Chlorophyll *a* in the Arabian Sea

Season	Cruise no.	Oxygen (µ M)	DELN (µ M)	Chl (mg m^{-3})
Intermonsoon	SK 91	17.5	3.72	8.3
Winter	SK 99	10.6	4.02	20
Southwest monsoon	SK 104	18.2	1.62	–

seen in nitrate distribution but not in dissolved oxygen (Figure 7). Increases in nutrients in surface layers due to upwelling result in increased productivity. For example, the primary productivity was 1760 mgC m^{-2} d^{-1} off Mangalore (12°30'N, 73°30'E), 660 mgC m^{-2} d^{-1} near Cochin (10°N, 75°35'E) and 440 mgC m^{-2} d^{-1} off Bombay[17]. This shows a patchiness in surface production. The intensity of upwelling along the southwest coast of India can be suppressed by land run-off[4,21]. Consequently, variable run-off may have caused the observed patchiness in productivity[4]. However, during intermonsoon it was 199 mgC m^{-2} d^{-1} near Cochin[17] which is considerably less than that in monsoon.

Table 1 shows the seasonal variability in average redox conditions (oxygen and nitrate as indicators) in the Arabian Sea. These are averages for the zone of denitrification, i.e. positive DELN. Results indicate relatively lower dissolved oxygen (11 µM) with relatively high DELN (4 µM) during winter. This is consistent with the average abundance of chlorophyll *a*. Although the oxygen levels between intermonsoon and monsoon did not differ greatly, the nitrate deficit during the former season was nearly twice that computed for monsoon.

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