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The oxygen minimum zone in the Arabian Sea during 1995

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Abstract

This paper focuses on the characteristics of the oxygen minimum zone (OMZ) as observed in the Arabian Sea over the complete monsoon cycle of 1995. Dissolved oxygen, nitrite, nitrate and density values are used to delineate the OMZ, as well as identify regions where denitrification is observed. The suboxic conditions within the northern Arabian Sea are documented, as well as biological and chemical consequences of this phenomenon. Overall, the conditions found in the suboxic portion of the water column in the Arabian Sea were not greatly different from what has been reported in the literature with respect to oxygen, nitrate and nitrite distributions. Within the main thermocline, portions of the OMZ were found that were suboxic (oxygen less than ~ 4.5 μM) and contained secondary nitrite maxima with concentrations that sometimes exceeded 6.0 μM, suggesting active nitrate reduction and denitrification. Although there may have been a reduction in the degree of suboxia during the Southwest monsoon, a dramatic seasonality was not observed, as has been suggested by some previous work. In particular, there was not much evidence for the occurrence of secondary nitrite maxima in waters with oxygen

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concentrations greater than 4.5 μM. Waters in the northern Arabian Sea appear to accumulate larger nitrate deficits due to longer residence times even though the denitrification rate might be lower, as evident in the reduced nitrite concentrations in the northern part of the basin. Organism distributions showed string relationships to the oxygen profiles, especially in locations where the OMZ was pronounced, but the biological responses to the OMZ varied with type of organism. The regional extent of intermediate nepheloid layers in our data corresponds well with the region of the secondary nitrite maximum. This is a region of denitrification, and the presence and activities of bacteria are assumed to cause the increase in particles. ADCP acoustic backscatter measurements show diel vertical migration of plankton or nekton and movement into the OMZ. Daytime acoustic returns from depth were strong, and the dawn sinking and dusk rise of the fauna were obvious. However, at night the biomass remaining in the suboxic zone was so low that no ADCP signal was detectable at these depths. There are at least two groups of organisms, one that stays in the upper mixed layer and another that makes daily excursions. A subsurface zooplankton peak in the lower OMZ (near the lower 4.5 μM oxycline) was also typically present; these animals occurred day and night and did not vertically migrate.

1. Introduction

This paper focuses on the characteristics of the oxygen minimum zone (OMZ) observed in the Arabian Sea over the complete monsoon cycle of 1995. Dissolved oxygen, nitrate, nitrite and density values are used to delineate the OMZ, as well as identify regions where denitrification is observed. The suboxic conditions within the northern Arabian Sea are documented, as well as biological and chemical consequences of this phenomenon. The oxygen deficient waters of the oxygen minimum zone (OMZ) are important because in extremely low oxygen environments, denitrification is a prominent respiratory process that converts nitrate, which is in a form of nitrogen readily available to most plants, into free nitrogen gas, which most plants cannot use. That this process is important in the Arabian Sea is demonstrated by the widespread occurrence of nitrate deficits (i.e., the difference between the nitrate concentrations expected if there were no denitrification and the sum of the observed nitrate and nitrite concentrations), a measure of the amount of inorganic nitrogen that has been converted into free nitrogen gas (Naqvi, 1994).

Richards (1965) showed that several important biogeochemical changes are involved in the change from "oxic" to "anoxic" conditions. The first of these processes is that during oxygen depletion, facultative bacteria switch over to the use of nitrate ions for oxidation of organic matter. Nitrate is reduced to molecular nitrogen, with nitrite as one of several intermediates. In the ocean, the major end-product is free nitrogen. This process, called denitrification is a major component of the nitrogen cycle (see Naqvi, 1994). Only nitrogen-fixing plants use free nitrogen, so denitrification represents a "sink" for combined nitrogen vis-à-vis the requirements of most phytoplankton. The suboxic zones in the Arabian Sea comprise one of the three major water column denitrification sites in the world ocean (e.g., Codispoti, 1989) and have an annual denitrification rate of 10–30 Tg N yr^{-1} (Mantoura et al., 1993; Naqvi et al., 1992). After an almost complete removal of nitrate and nitrite from the ocean, sulfate ions serve as the next preferred reduction substrate, leading to production of hydrogen sulfide or true anoxic conditions. This stage is most often reached in bottom sediments and rarely is reached in the open ocean. Regions which experience denitrification but no hydrogen sulfide production are referred to as "suboxic".

Strong OMZs have substantial impacts on abundance and distribution of pelagic organisms (Vinogradov and Voronina, 1961; Longhurst, 1967; Brinton, 1979; Weikert, 1982; Sameoto, 1986; Böttger-Schnack, 1996; Saltzman and Wishner, 1997a,b), which, in turn, may have important consequences for carbon cycling and the vertical flux (Wishner et al., 1990,1995,1998). In the Arabian Sea during the US JGOFS study, organism distributions showed strong relationships to oxygen concentrations, especially in locations where the OMZ was pronounced; but the biological responses to the OMZ varied with the type of organism. Also, waters with high nitrate deficits have a reduced potential to support phytoplankton growth and N/P ratios are low in the Arabian Sea (Morrison et al., 1998). Therefore, it is important to know the temporal and spatial variability of oxygen deficient conditions in the Arabian Sea.

In this paper, the OMZ structure of the Arabian Sea over a complete annual (monsoonal) cycle is presented using an internally consistent, high-quality data set as an aid to the interpretation of the US JGOFS Arabian Sea Process Study results. Overall, the conditions found in the suboxic portion of the water column in the Arabian Sea were not greatly different from what has been reported in the literature with respect to oxygen, nitrate and nitrite distributions. The areas where we are confirming the results of other investigators, as well as where our results differ with the results of others, are discussed. Finally, some preliminary results on the biological effects of the OMZ are discussed. The presence of a very high biomass of diel vertical migrators that moved between the surface waters at night and the suboxic waters during the day was a surprising finding from the US JGOFS sampling.

2. Scientific background

The semi-annual reversal in wind stress associated with the monsoon, water mass intrusions from marginal seas and the other oceans, and the fact that this basin has no opening to the north and therefore no subtropical convergence or deep water formation, give the upper waters of the Arabian Sea a unique thermohaline structure and circulation (Wyrtki, 1971; Morrison and Olson, 1992; Morrison et al., 1998). The complex water mass structure is due in part to advection and interleaving of water masses, and in part to formation of high-salinity waters in the Red Sea, Persian Gulf and northern portion of the basic (Arabian Sea Water) that sink to moderate depths in the central basin. Wyrtki (1971) provided an overall view of water mass structure for the Indian Ocean. More detailed discussions of the water masses in the northern Arabian Sea are given in Morrison et al. (1998), Morrison and Olson (1992) and in several of the references mentioned therein. With respect to the oxygen minimum zone

(OMZ) and, in particular, the suboxic portion of the OMZ, some basic characteristics need to be understood.

(1) The upper boundary of the OMZ often occurs at sigma-theta values ($\sim 24.8\sigma_\theta$) that are characteristic of the salinity maximum of Arabian Sea Water (ASW). This feature has a maximum depth of ~ 150 m in the northern Arabian Sea. During the NE monsoon, this water mass can be replenished by convective processes in the northern Arabian Sea (Morrison et al., 1998). Thus, the upper boundary of the OMZ receives some direct re-oxygenation as a consequence of evaporative cooling and convection during the NE monsoon. Lower salinity water with σ_θ values in the range of ASW reaches the sea surface in coastal upwelling that occurs during the SW monsoon along the coast of Oman (Morrison et al., 1998), and convective mixing of these waters under the strong winds of the SW monsoon should also help to re-oxygenate the upper waters of the OMZ.

(2) The "core" of the suboxic layers with elevated nitrite values is more or less coincident with the salinity maximum layer of Persian Gulf Water (PGW) that has its "core" at a density of $\sim 26.6\sigma_\theta$. Pure, high-salinity PGW mixes quickly with ambient waters in the northern Arabian Sea so that the outflow from the Persian Gulf is actually only a minor component of this water mass, but it gives it a salinity marker that appears to be closely associated with the suboxic portions of the OMZ (Morrison et al., 1998).

(3) The bottom of the suboxic portions of the OMZ are roughly coincident with the characteristic density ($\sim 27.2\sigma_\theta$) of Red Sea Water (RSW). This high-salinity outflow from the Red Sea sinks to depths of ~ 750 m and forms a salinity maximum in portions of the Indian Ocean. This maximum is weak or absent from our stations in the northern Arabian Sea, suggesting that RSW mixes quickly with other water masses found at this density within the Arabian Sea, such as Indian Central Water (You and Tomczak, 1993) and North Indian Intermediate Water (Kumar and Li, 1996).

(4) Warren (1994) reviewed evidence that suggests new production in the Arabian Sea is not anomalously large, and is therefore not a major factor in generating the suboxic layer. He suggested that physical factors, such as the distance from the oxygen sources, were probably more important. While his view has merit, recent results (Smith et al., 1998) may cause upward revision in estimates.

(5) The combination of relatively weak aeration, presumably arising from a combination of lack of an opening to the north, sub-thermocline source waters that have naturally low dissolved oxygen content originating in the Southern Ocean (Swallow, 1984; You and Tomczak, 1993; Warren, 1981) or Banda Sea (Swallow, 1984), and relatively high biological productivity combine to create suboxic waters.

Fig. 1 shows the standard US JGOFS Arabian Sea station sampling grid in relation to the zone (shaded area) where the work of Naqvi and colleagues (e.g., Naqvi, 1991,1994) suggests that average secondary nitrite maximum values are $\geqslant 1$ μM. These features are called secondary nitrite maxima because they normally occur deeper in the water column than the primary nitrite maxima that are a typical feature

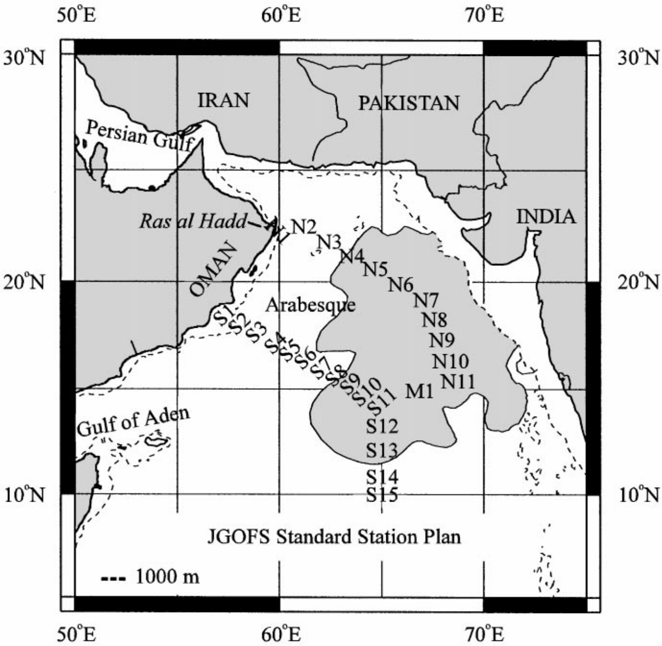


Fig. 1. Location and names of the standard station position for the US JGOFS Arabian Sea Process Study. The shaded region underlying the station grid gives a depiction of the horizontal extent of the quasi-permanent secondary nitrite maximum regions described by Naqvi (1991).

near the base of the photic zone and which arise from phytoplankton reduction of nitrate, nitrification, or both (Codispoti and Christensen, 1985). Such nitrite concentrations in suboxic water (dissolved oxygen $\lesssim 0.1$ ml/l or $\lesssim 4.5\ \mu M$ or $\lesssim 4.5\ \mu mol\ kg^{-1}$) indicate that denitrification is a prominent respiratory process. Naqvi et al. (1992) point out that, unlike the denitrification zone off Peru (Codispoti and Packard, 1980), the zones of lowest oxygen and highest primary production are geographically separated in the Arabian Sea. The shaded region in Fig. 1 indicates the horizontal extent of the main denitrification zone, and it is obvious that it lies offshore of the upwelling that is most intense adjacent to the Arabian Peninsula. This situation has led to speculation about how organic matter is supplied to the denitrification zone, and the assumption is that horizontal processes are important in supplying such material (Naqvi et al., 1992). It also should be noted that transient secondary nitrite maxima occur outside of the shaded zone (Morrison et al., 1998).

3. Data and methods

The primary platform for the US JGOFS Arabian Sea Process Study (ASPS) was the R/V *Thomas G. Thompson*; hence, the cruise designations appear as TN0XX where

Table 1
JGOFS Arabian Sea process study crusies

Cruise	Dates	Monsoon period
TN039	09/17/94–10/07/95	Fall Intermonsoon
TN043	01/08/95–02/11/95	late NE monsoon
TN045	03/14/95–04/08/95	Spring Intermonsoon
TN049	07/18/95–08/13/95	mid-SW monsoon
TN050	08/14/95–09/13/95	late SW monsoon
TN053	10/29/95–11/25/95	Fall Intermonsoon
TN054	11/30/95–12/28/95	early NE monsoon

XX represents the cruise number. The ASPS occupied a standard sampling grid (Fig. 1) comprised of a mixture of short, intermediate and long stations. In general, more than one hydrographic cast was made at every station, and, at the long stations, many (often > 10) casts were made with the hydrographic rosette. Sometimes, the ship was allowed to drift during the long stations in order to follow drifting arrays. Most of the casts were within 2–5 km of the standard locations. All of the hydrographic, dissolved oxygen and nutrient data collected, as well as the standard methods employed to collect and calibrate these data, can be found in the US JGOFS Program Database at the Woods Hole Oceanographic Institution (http://www1.whoi.edu/jgofs.html). The ASPS was unique in that it collected areally extensive, high-quality hydrographic data during a complete annual monsoonal cycle (Table 1). For a more complete description of the hydrographic data see Morrison et al. (1998).

With the exception of a few observations taken with larger volume Niskin or Go-Flo bottles during TN039 (the set-up and calibration cruise), all of the dissolved oxygen and nutrient data discussed in this paper were taken with a hydrographic rosette equipped with 24 10-l Niskin bottles. In general, the methods employed for the bottle salinity, Winkler dissolved oxygen, and nutrient analyses did not differ significantly from those described in the US JGOFS protocols (SCOR, 1996). In addition, azide was added to the Winkler oxygen pickling reagents to destroy nitrite that can be present in relatively high concentrations in the Arabian Sea. On cruises prior to TN050, oxygen standardizations were run using reagents that did not contain azide, but discussions and tests suggested that it would be preferable to standardize with azide, despite some confusion in the literature on this matter. We switched procedures beginning with cruise TN050. Tests suggest that the maximum change in oxygen concentrations arising from this change would occur at the highest oxygen concentrations and be ~ 0.5 μM or less.

Traditionally, the co-occurrence of low Winkler oxygen concentrations and high nitrite levels have been used determine the extent of oxygen deficient zones. Winkler oxygen methods tend to give high results at low concentrations found in oxygen deficient zones (e.g., Broenkow and Cline, 1969; Codispoti and Christensen, 1985). During TN039, comparisons were made between the colorimetric dissolved oxygen method of Broenkow and Cline, which is designed to sample the 0 to ~ 25 μM range,

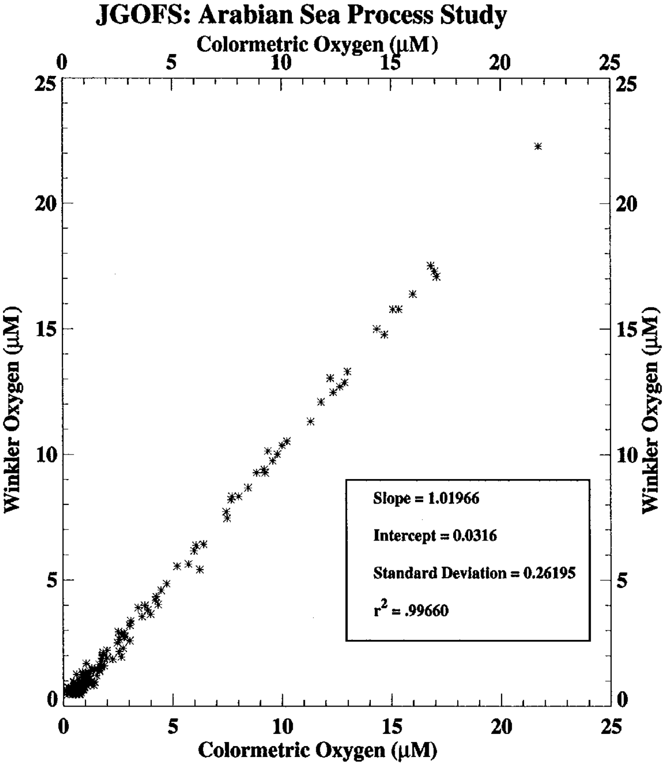


Fig. 2. Comparison of the Scripps Institute of Oceanography/Oceanographic Data Facility (SIO/ODF) automated Winkler titration method with the low-concentration colorimetric method developed by Broenkow and Cline (1969) during the JGOFS Arabian Sea set-up and calibration crusise, TN039.

and the automated Winkler method developed by personnel of the oceanographic data facility (ODF) at Scripps Institution of Oceanography. The results of this comparison (Fig. 2) suggest that any bias was less than ~ 0.05 μM. Sea-water blanks were run in only a few cases, so the oxygen data in this report are (as usual) not corrected for such blanks. The precision of the SIO Winkler method also appears to be better than ~ 0.05 ml/l (~ 2.3 μM) in the low range (Fig. 2). Therefore, we have confidence in the use of the Winkler and nitrite data to study the extent and degree of oxygen deficient conditions in the eastern Arabian Sea using data from all available US JGOFS cruises. These measurements are precise enough to measure values that are near the threshold values of 1.2–3.8 μM required for the onset of denitrification (Devol, 1978).

Hydrographic profiles during the JGOFS process cruises generally included a transmissometer and fluorometer interfaced with the CTD to measure beam attenuation due to particles (c_p) and chlorophyll *a* fluorescence. A detailed description of the methods used and the distribution of these two parameters in the upper 150 m of the Arabian Sea can be found in Gundersen et al. (1998). Beam attenuation is correlated approximately linearly with the mass abundance of particulate matter $\lesssim 20\ \mu M$, so it is good proxy for the abundance of most small plankton, including bacteria $\gtrsim 0.5\ \mu M$ (Pak et al., 1988; Chung et al., 1996). Zooplankton were collected using MOCNESS tows (see Wishner et al., 1998; and Smith et al., 1998, for processing and calibration details). An oxygen sensor (Seabird SBE 13) was included among the suite of instruments on the deep MOCNESS. Backscatter intensity data from the acoustic Doppler current profiler (ADCP) were calibrated (Flagg and Smith, 1985; Flagg and Kim, 1998) and corrected for square-law-spreading and attenuation.

4. Results and discussion

4.1. Thickness of the oxygen deficit zone

Fig. 3 shows the thickness of the oxygen deficit zone and its position in the water column relative to the sea surface. The 4.5 μM "suboxic" boundary (delineated in Fig. 3 by bars) is an important biological boundary where oxygen apparently becomes physiologically limiting to many bacteria, causing a shift from oxygen respiration to nitrate reduction and denitrification (Devol, 1978). Oxygen becomes limiting for many higher organisms at even higher levels, resulting in their exclusion from this zone, except for temporary residence by vertical migrators as discussed later in this paper.

Vertical sections of the distribution of temperature, dissolved oxygen, nitrate and nitrite are used in order to investigate the vertical distribution of the OMZ and the resulting areas of denitrification. Sections taken during the height of the NE monsoon and SW monsoon are presented as typical for the entire monsoon cycle. While there is considerable variability, no seasonal trend associated with the monsoon is readily observable. This might be expected as the OMZ is located directly below a strong permanent thermocline. Unfortunately, no data were taken within the Gulf of Oman or within 100 nm of the Indian coast. Therefore, we will be able to discuss the relationship of the suboxic and denitrification zones with the Oman upwelling zone, but not be able to map the distributions in the entire northeastern Arabian Sea.

Temperature, dissolved oxygen, nitrate and nitrite distributions along the northern ASPS section during the NE monsoon (TN043) and during the SW monsoon (TN050) are presented in Figs. 4 and 5, respectively. Typically, a week to a week and a half was required to complete a section, which could lead to some of the observed variability. The temperature sections display a strong permanent thermocline at approximately 100 m. The surface mixed layer is approximately 80–100 m thick during the NE monsoon, shoaling to less than 50 m in the central basin during the SW monsoon. Upwelling and no mixed layer were observed between stations N1–N3 during the SW monsoon. In addition, mixed layer temperatures greater than 25°C begin south of station N8 during the NE monsoon, while seasonal heating warmed the mixed layer during the SW monsoon, so that temperatures in excess of 25°C were found as far north as station N2. Below the main thermocline, the isotherms are essentially horizontal during the late NE monsoon, while during the late SW monsoon, the

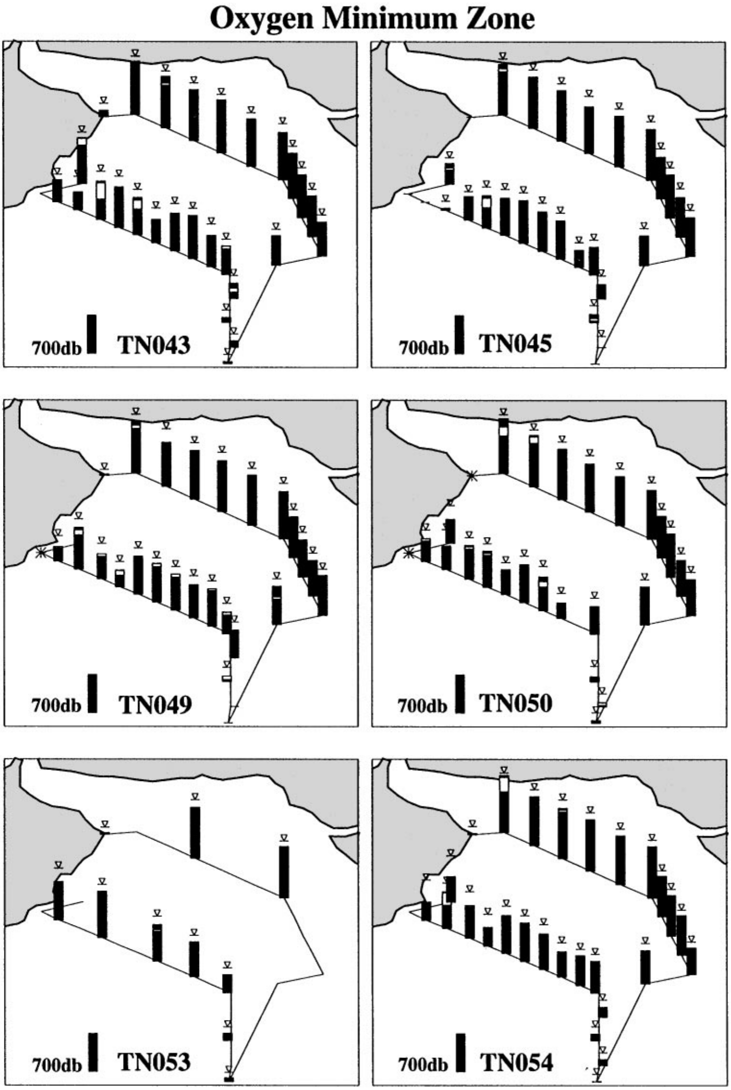


Fig. 3. Thickness of the suboxic (oxygen deficit) zones as seen at the ASPS stations. This figure shows the depth ranges where the dissolved oxygen is less than 4.5 μM (0.1 ml/l). The thickness of the OMZ and the existence of relative oxygen maxima (white space in the bar) within the zone relative to the sea surface are shown. ($\underline{\nabla}$ indicates the sea surface and $*$ indicates where no suboxic zone was observed.)

isotherms decrease in depth the further the station is off the coast of Oman, indicating broad southward flow through this section during the SW Monsoon. The suboxic zone (oxygen concentrations less than ~ 4.5 μM) is observed along the entire length of this section. It varies in thickness from approximately 1000 m along the Oman coast to approximately 800 m at the southernmost station along this section. In

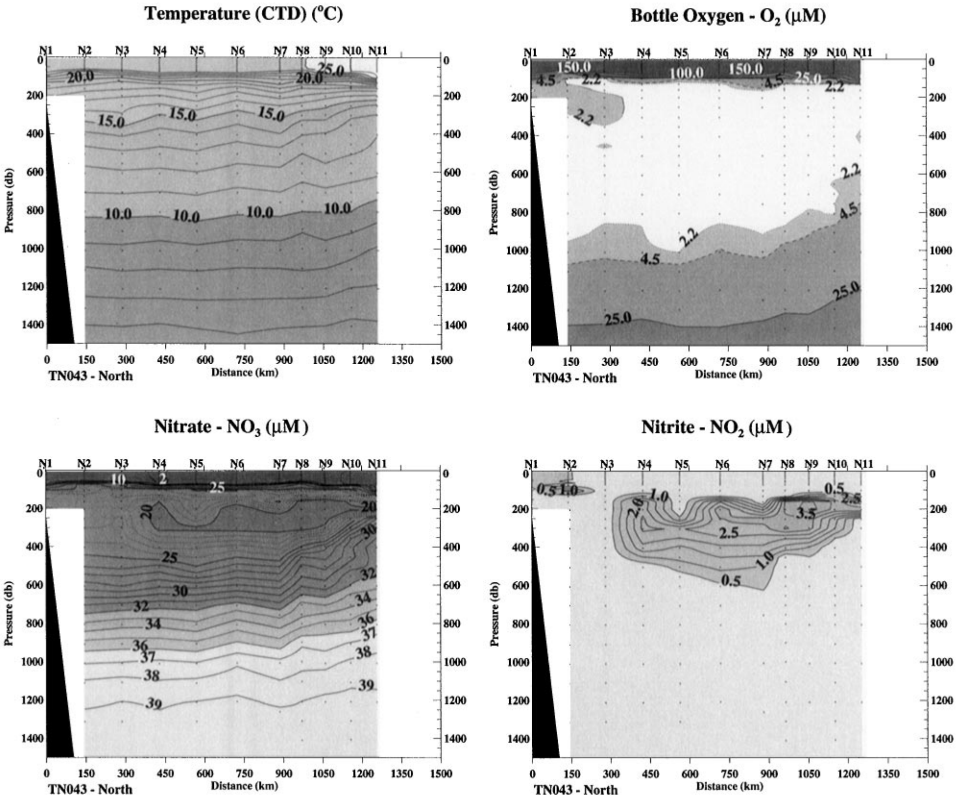


Fig. 4. Temperature, dissolved oxygen, nitrate and nitrite distributions along the nothern JGOFS section during the NE monsoon (TN043).

addition, along the Oman coast a subsurface tongue of water with slightly higher oxygen content a subsurface tongue of water with slightly higher oxygen content associated with outflow from the Persian Gulf is observed at 200–300 m. The nitrate minimum is observed at approximately 250 m along this section. Nitrate concentrations less than 20 μM are found as far north as N4 during the NE monsoon. During the Intermonsoon and early SW monsoon (not shown here), nitrate concentrations less than 20 μM are found only as far north as station N6. By the late SW monsoon, concentrations less than 20 μM are once again found as far north as N4. Secondary nitrite maxima, with concentrations in excess of 0.5 μM are observed as far north as station N4 during the entire year. There is considerable variability within this maximum, but in general the largest concentrations, indicating perhaps the highest denitrification rates (Codispoti and Packard, 1980), are observed at the southern end of the section. The nitrate minimum and nitrite maximum occur at approximately the same depth, but the two do not coincide laterally; the highest nitrite concentrations occur near the southern end of the section. Nitrite concentrations reflect ongoing

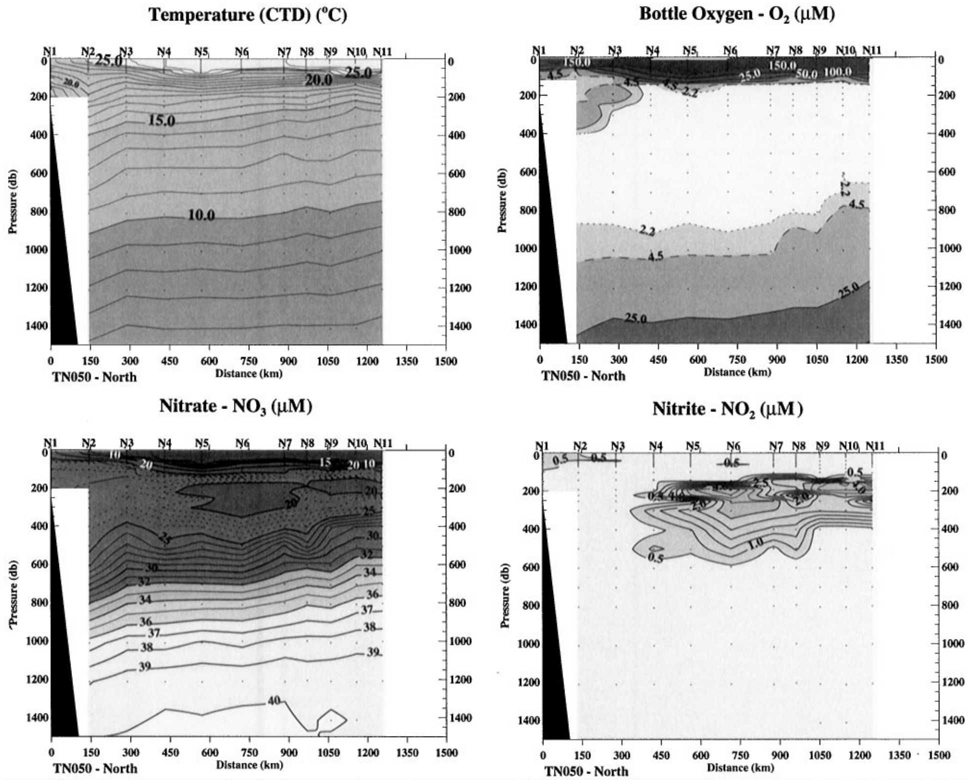


Fig. 5. Temperature, dissolved oxygen, nitrate and nitrite distributions along the northern JGOFS section during the SW monsoon (TN050).

denitrification, whereas reduction all the way to free nitrogen produces nitrate deficits that are conservative and which may accumulate even as denitrification rates vary (Naqvi, 1994). The waters in the northern Arabian Sea accumulate larger nitrate deficits possibly due to longer residence times in the suboxic zone even though the denitrification rate might be lower as evidenced by the observed low-nitrite concentrations in the northern parts (Naqvi, 1994).

Temperature, dissolved oxygen, nitrate and nitrite distributions along the southern US JGOFS Arabian Sea section during the NE monsoon (TN043) and during the SW monsoon (TN050) are presented in Figs. 6 and 7, respectively. The temperature sections display a strong permanent thermocline at approximately 100 m during the late NE monsoon, with temperatures in excess of 25°C as close to the Oman coast as station S4. By the time of the late SW monsoon, the picture has changed considerably. South of station S9, the mixed layer is essentially unchanged. Northwest of this, the mixed layer has shallowed to approximately 75 m from stations S8–S5. Inshore of station S5, and intense upwelling is observed with isotherms rising approximately

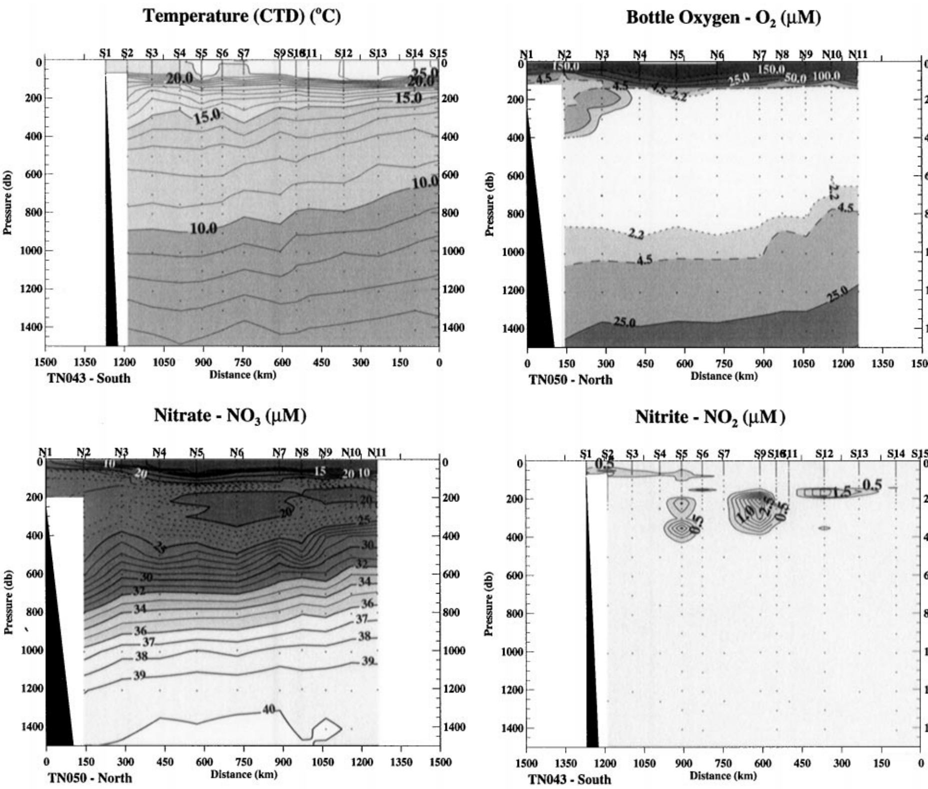


Fig. 6. Temperature, dissolved oxygen, nitrate and nitrite distributions along the southern JGOFS section during the NE monsoon (TN043).

100–150 m. Also, close to the Oman coast at Ras al Hadd (station N1 is just off of Ras al Hadd, see Fig. 1), a subsurface southwest-flowing jet of PGW (Morrison, 1997) is observed at 150–400 m depth during the late NE monsoon. During the late SW monsoon, this jet does not reach as far south as this section. Beneath the thermocline, the isotherms generally decrease in depth further off the coast. This suggests a broad anticyclonic flow below the thermocline that is fed by northeastward flow along the coast of Oman and by southwestward flow around Ras al Hadd. In general, dissolved oxygen concentrations on the southern section are higher than on the northern section. In this section only isolated pockets of oxygen concentrations less than 2.2 μM are observed. While oxygen concentrations were somewhat higher, the OMZ still had concentrations appear to be closer to the coast of Oman along this section. This coastward displacement appears to be associated with the shape of the gyre boundary (Bruce, 1983). Also, below the euphotic zone, there are only isolated patches of nitrate less than 20 μm and nitrite in excess of 0.5 μM, suggesting significantly less denitrification than observed along the northern section. This suggests that the higher

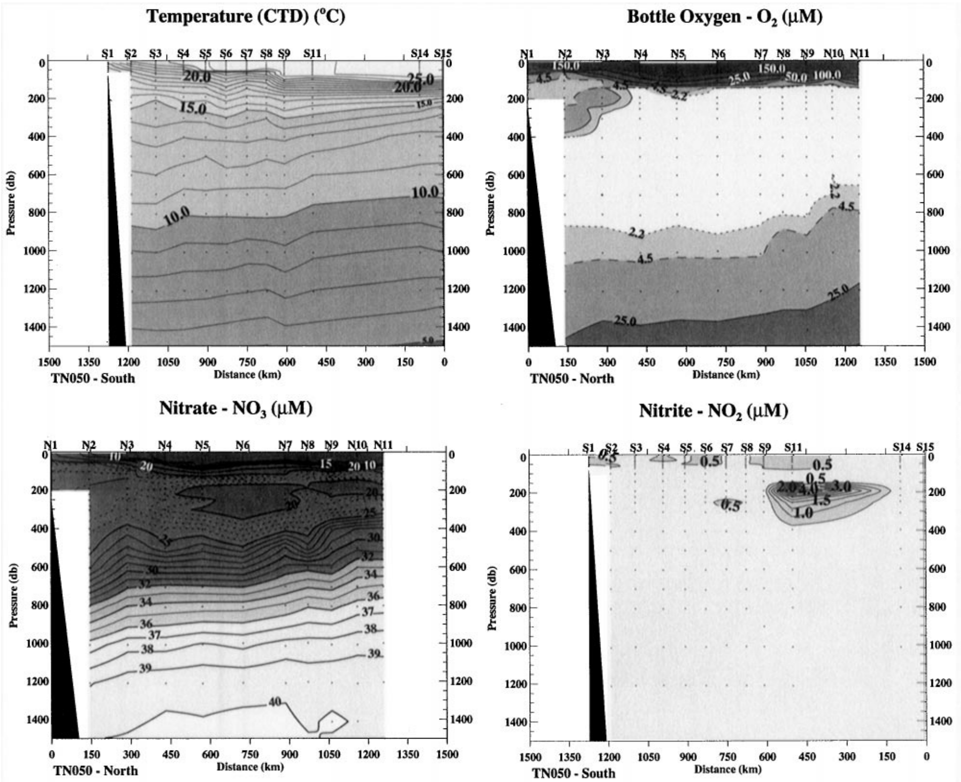


Fig. 7. Temperature, dissolved oxygen, nitrate and nitrite distributions along the southern JGOFS section during the SW monsoon (TN050).

residence times within the northern extremes of the basin are needed for the low-oxygen concentrations found within the Indian Central Water to become suboxic.

4.2. Denitrification

As discussed above, the co-occurrence of suboxic conditions and nitrite maxima are signs that denitrification is the dominant respiratory pathway in operation and that fixed nitrogen (mainly in the form of nitrate and nitrite) is being reduced to free nitrogen gas (Olsen, 1981). Qualitatively this can be seen by examining individual profiles of these properties versus pressure. Plots of nitrate, nitrite, nitrate-deficit and dissolved oxygen verses pressure (Fig. 8) are shown for stations from the "core" of the secondary nitrite maximum (see Fig. 1). The extensive nitrate minimum centered in the low oxygen waters at ~ 200 m is indicative of denitrification and nitrate reduction. The secondary nitrite maximum is centered in the low oxygen waters at ~ 200 m. The association of high nitrite and low oxygen is evident, but the nitrate

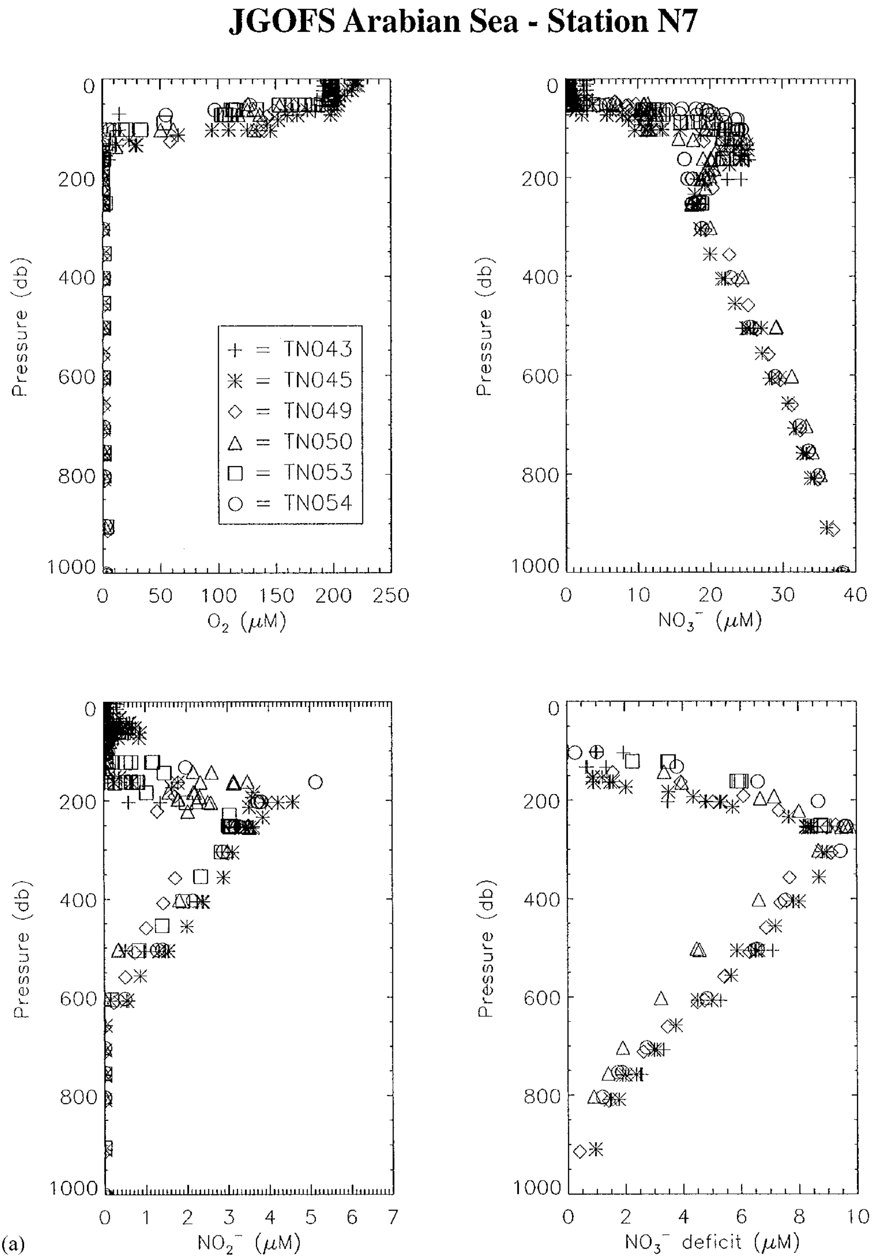
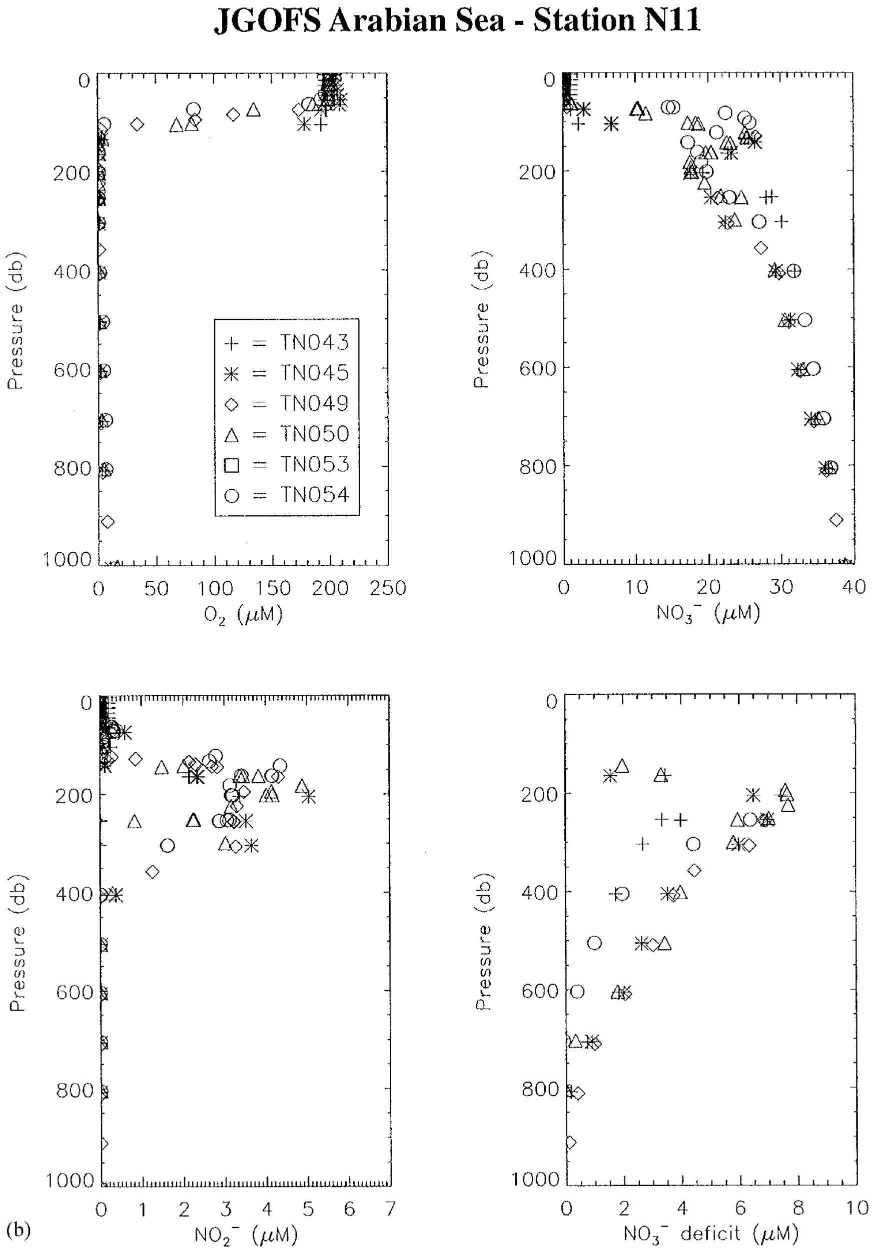


Fig. 8. Plots of nitrate, nitrite, nitrate deficits and dissolved oxygen versus depth for station (a) N7, (b) N11, (c) M1 and (d) S11, within the "core" of the secondary nitrite maximum. Fig. 1 shows the station location. Nitrate deficits were calculated using the method described by Naqvi (1994). (Note: Negative nitrate deficits are not plotted.)



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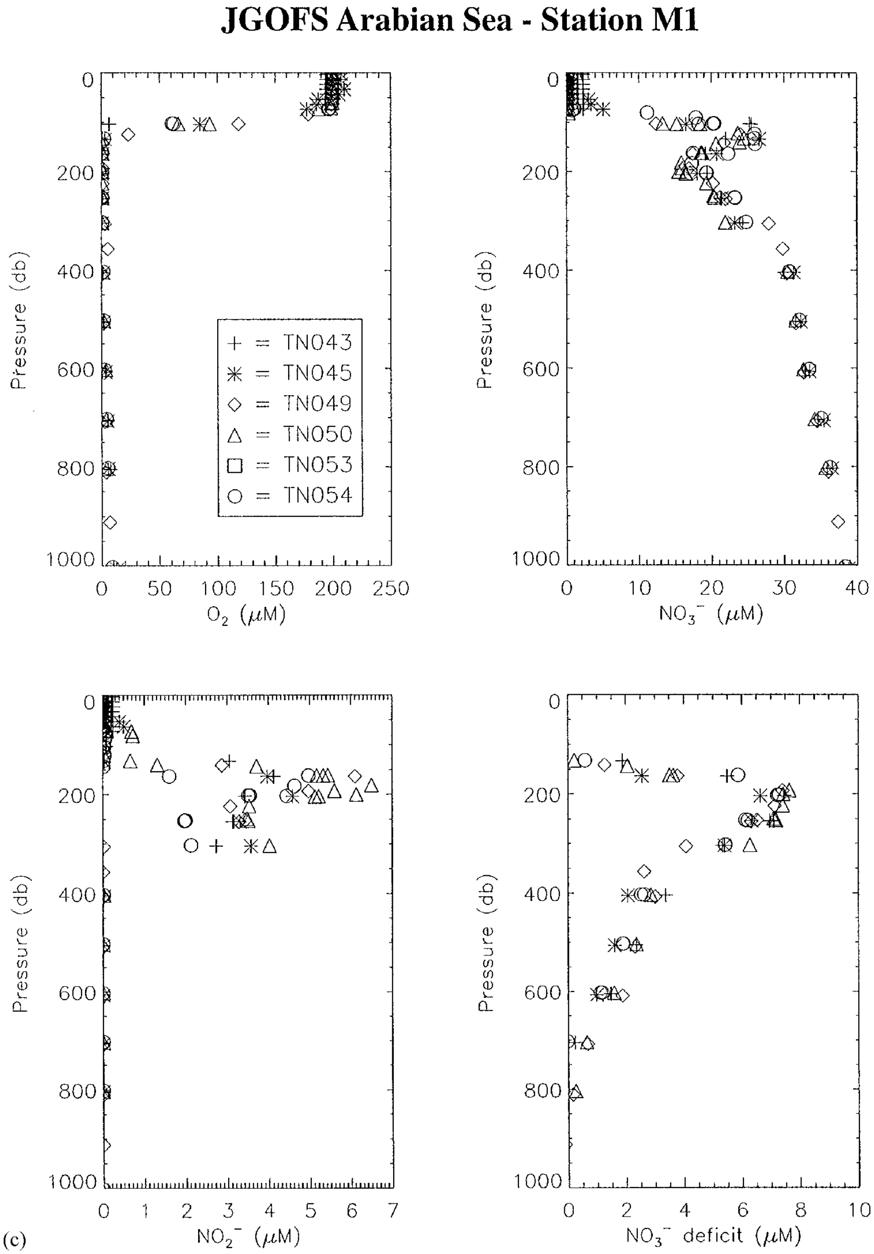

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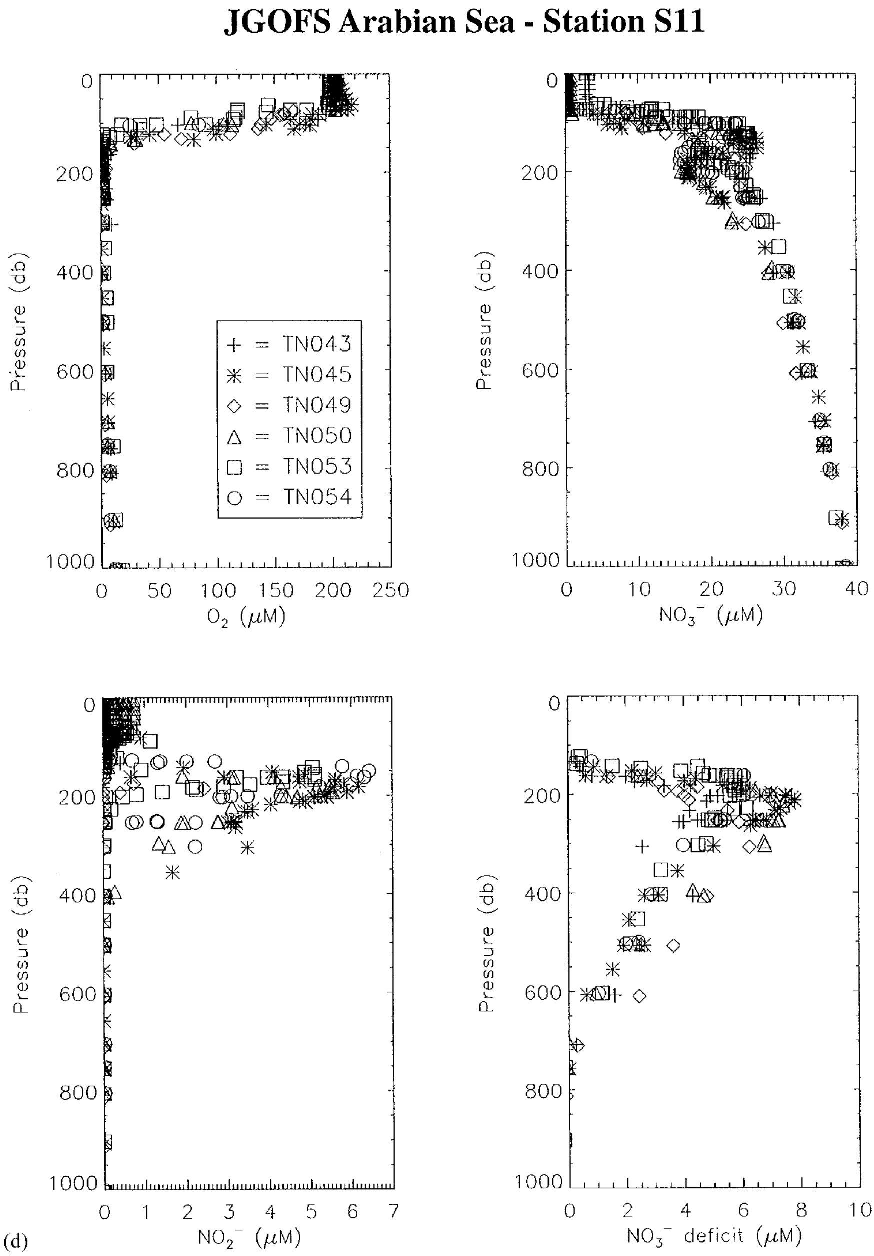


Fig. 8. Continued.

minima that arise from denitrification are not completely compensated by the associated nitrite maxima, as indicated by the companion nitrate-deficit profiles.

Naqvi et al. (1992) suggest that suboxic conditions are more developed during the NE monsoon than during the SW monsoon. The dogleg portion of the southern JGOFS section (Figs. 4–7; Stations S11–S15) coincides with a section occupied by the Indian JGOFS program during the Spring Intermonsoon season (April–May) of 1994 and NE monsoon (February–March) and SW monsoon (July–August) of 1995 (de Souza et al., 1996). Their vertical sections show considerable temporal variability in dissolved oxygen, progressing from suboxic values in the NE monsoon, increasing through the Spring Intermonsoon, to reach concentrations of 20 μM in the OMZ in the SW monsoon. As seen in the vertical sections of dissolved oxygen (Figs. 4–7), this variability was not observed on the US JGOFS cruises.

Composite nitrite versus oxygen concentrations for pressures greater than 100 db for all of the ASPS cruises (Fig. 9) suggests that the buildup of high nitrite concentrations in the secondary nitrite maximum is associated with suboxic waters. This secondary nitrite maximum with concentrations that sometimes exceed 6 μM is a typical feature within suboxic layers (Deuser et al., 1978; Sen Gupta and Naqvi, 1984; Naqvi, 1991).

Fig. 9 can be used to examine further the idea that there is a seasonality in suboxic conditions in the Arabian Sea. Indian JGOFS data (de Souza et al., 1996) suggest that a secondary nitrite layer also can occur at dissolved oxygen concentrations of 5–10 μm. We find few secondary nitrite maxima associated with oxygen values > 5 μM in the US JGOFS data (Fig. 9). In general, our data do not have a seasonal variability in secondary nitrite maxima and associated dissolved oxygen as observed by de Souza et al. (1996). In contrast, there is a definite seasonality in the primary nitrite maxima found near the bottom of the photic zone.

4.3. Intermediate Nepheloid Layers in the OMZ

The concentration of particulate matter (and thus beam attenuation due to particles, c_p) generally decreases rapidly below the surface mixed layer (Gardner et al., 1995; Gundersen et al., 1998). In the Arabian Sea, however, there were regions where a secondary particle maximum, or intermediate nepheloid layer (NL), occurs between 150 and 350 m (Fig. 10), containing particle concentrations comparable to some surface values. Data in Fig. 10 are from the Spring Intermonsoon season (TN045), but similar distributions occurred at other times of the year.

The position of the INL was near the top of the OMZ (Figs. 4–7). The low-oxygen zone was nearly ubiquitous in the region of the Arabian Sea that we sampled, but the INLs were not, so it would appear that low oxygen is not a sufficient condition for the development of INLs. INLs have been observed in low oxygen zones in the Arabian Sea previously by Naqvi et al. (1993), and off the coast of Peru by Pak et al. (1980). Naqvi et al. (1993) demonstrated that the INL in the Arabian Sea is tightly coupled with the secondary nitrite maximum and denitrifying conditions, and not solely low-oxygen concentrations. Our data support this correlation. For example, in Fig. 10 the oxygen profile at station N3 shows low values below 130 m, but no nitrite peak in

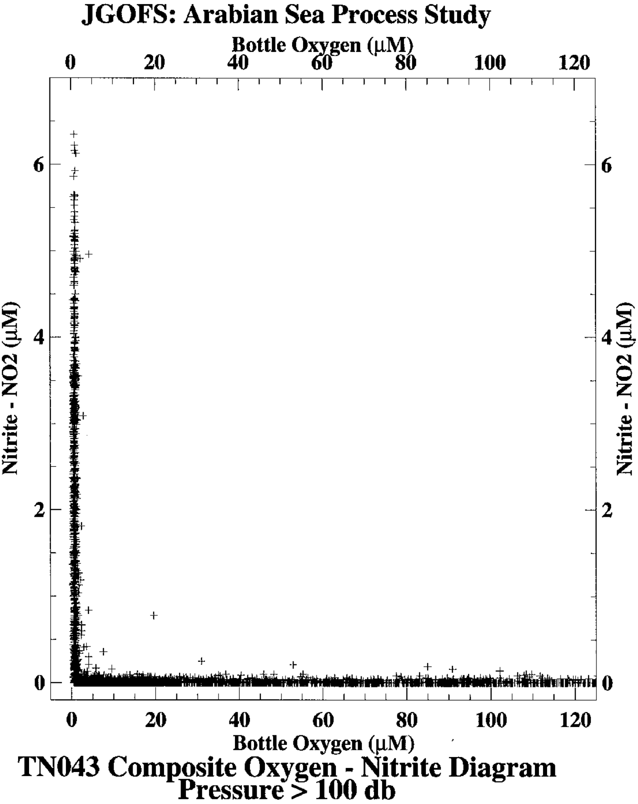


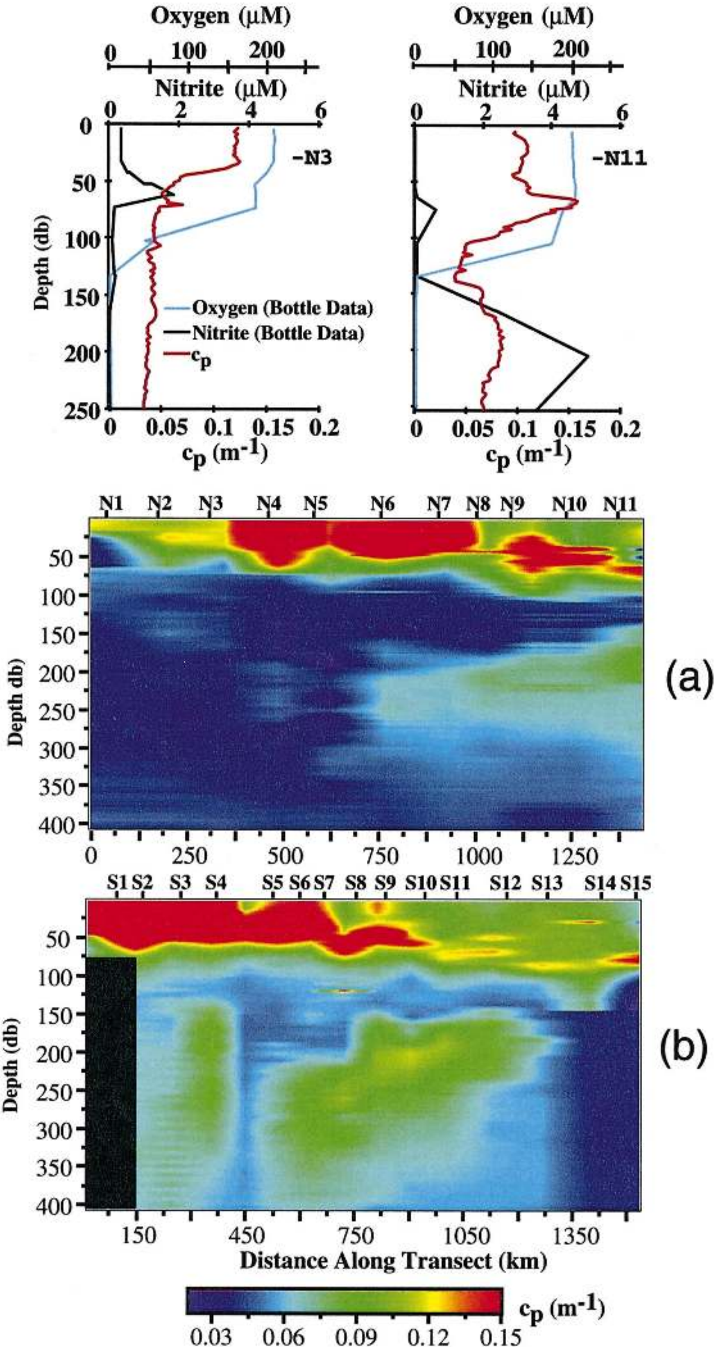
Fig. 9. Composite plot of nitrite versus dissolved oxygen concentration for all of the JGOFS cruises for pressures greater than 100 db.

the OMZ. No INL is seen in the OMZ at that site either. At N11 there is a nitrite peak of > 5 μM at 200 m and the INL is strong at that depth. In general, the regional extent of INLs in our data (Fig. 10) correspond well with the region of quasipermanent, secondary nitrite maximum outlined in Fig. 1 by Naqvi (1991). This is a region of denitrification, and we assume that the presence and activities of bacteria are causing the increase in particles.

Seasonal variability in the intensity of the INL also was observed. During the SW monsoon (TN049 and 50) and Spring Intermonsoon (TN045), the maximum c_p signal was roughly 25% greater than during the two NE monsoon cruises (TN043 and TN054).

4.4. Biological effects of the OMZ

In the Arabian Sea during the ASPS, organism distributions showed strong relationships to the oxygen profiles, especially in locations where the OMZ was


Oxygen (μM)
0 100 200
Nitrite (μM)
0 2 4 6
Depth (db)
0 50 100 150 200 250
-N3
-N11
Oxygen (Bottle Data)
Nitrite (Bottle Data)
c_p
0 0.05 0.1 0.15 0.2
c_p (m^{-1})
N1 N2 N3 N4 N5 N6 N7 N8 N9 N10 N11
Depth db
50 100 150 200 250 300 350 400
0 250 500 750 1000 1250
(a)
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S15
Depth (db)
150 450 750 1050 1350
Distance Along Transect (km)
(b)
0.03 0.06 0.09 0.12 0.15
c_p (m^{-1})

pronounced, but the biological responses to the OMZ varied with the type of organism.

Several distribution patterns were apparent: (1) exclusion from the suboxic (< 4.5 μM) core of the OMZ (see Fig. 3) of most zooplankton biomass and many zooplankton and nekton species and groups, but, paradoxically, (2) the occurrence of extremely high abundances of a few species of diel vertical migrators at depth during the daytime, well within the suboxic zone, (3) organism-specific (and probably species-specific) distribution boundaries at the upper and lower edges of the OMZ, probably associated with particular oxyclines, and (4) the appearance of a subsurface abundance peak for many organisms and particles in the lower OMZ associated with the oxygen gradient between 2.3 and 4.5 μM (0.05 and 0.1 ml/l). These biological patterns, described further below, were elucidated primarily from cruises TN043 (January 1995, late Northeast monsoon), TN045 (March, Spring Intermonsoon), TN050 (August–September, late Southwest monsoon), and TN054 (December, early Northeast monsoon). During these four cruises, vertically-stratified MOCNESS plankton tows (152 μm mesh nets) were made into the OMZ to 1000 m depth at the 6 JGOFS long stations spanning the Arabian Sea Basin (S2, S4, S7, S11, S15, and N7), and the data are available on deep water and surface mesozooplankton biomass and distributions (Gowing and Wishner, 1998; Smith et al., 1998; Wishner et al., 1998). Additional biological information on the larger nektonic animals during this time comes from work by Madin et al. (1997) during other cruises in 1995 to some of these same locations.

Oxygen values below about 4.5 μM that extended over vertical ranges of hundreds of meters are associated with the major distributional responses of the mesozooplankton and nekton, as also seen in other regions such as the Eastern Tropical Pacific Ocean. In the Arabian Sea, most zooplankton are absent from the suboxic part of the water column, and biomasses at depth (except for the daytime vertical migrators) were extremely low (Fig. 11) (Smith et al., 1998; Wishner et al., 1998). Presumably, most organisms are unable to tolerate the extremely low-oxygen conditions and are excluded from the OMZ by physiological constraints. Most of the biomass occurs in the upper water column, and the percent of the water column zooplankton biomass (0–1000 m) that resides in the upper well-oxygenated surface layer (0–1000 m) at night is highest in locations where a large percent of the deep water column was suboxic (Fig. 12; significant positive Spearman correlation, $p = 0.01$). However, the total water column biomass (0–1000 m) and the zooplankton biomass of the upper well-oxygenated layer are not apparently affected by the OMZ, suggesting that normal mixed layer processes control surface zooplankton abundances both above and away from OMZs. The exclusion of larger organisms from OMZ depths suggests that sinking material would transit this zone relatively rapidly, unaltered by consumers, and arrive at depth as a relatively fresh food source for deeper organisms.

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Fig. 10. Intermediate nepheloid layer during the Spring Intermonsoon. At station N11, a secondary nitrite maximum was observed. This increase, missing at station N3, is correlated with zones of denitrification. The scale has been adjusted to highlight the subsurface features. The c_p sections of beam attenuation due to particles (c_p) are from the (a) northern and (b) southern transects from the Spring Intermonsoon.

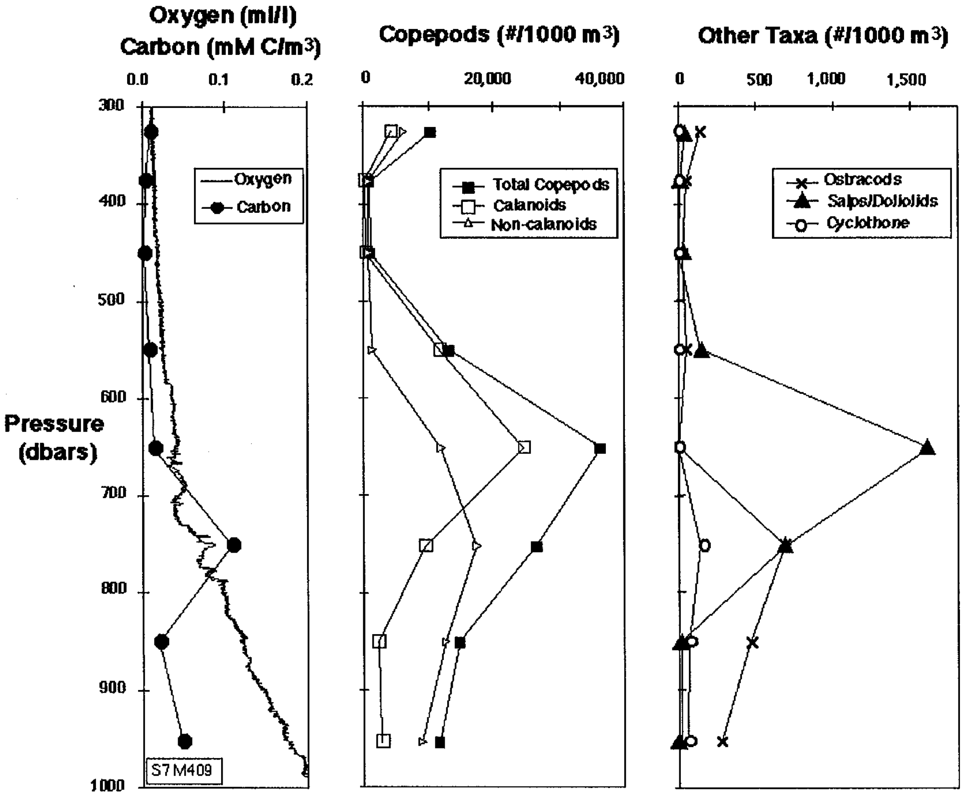

Fig. 11. Profiles of oxygen and mesozooplankton components from a vertically-stratified MOCNESS night tow (double 1 m^2 MOCNESS system, 153 μm mesh nets) at station S7 during crusise TN054 (early Northeast Monsoon) on 17 December 1997. The oxygen profile comes from the oxygen sensor on the MOCNESS calibrated to values obtained by the Winkler procedure on bottle samples from the CTD casts at the same station. Carbon values for total mesozooplankton are from nighttime size-fractionated dry weight measurements from each of the MOCNESS samples (see Wishner et al., this volume, for methods). Abundances of copepods and other taxa are from counts of sub-samples using a dissecting microscope. *Cyclothone* is a genus of mid-water fishes. Mesozooplankton biomass and the abundances of different taxa showed peaks near the depth of the oxygen gradient between 2.3 and 4.5 μM (0.05 and 0.1 ml/l) close to the base of the OMZ, but the depths of these peaks varied between groups, probably because of physiological differences in oxygen requirements.

The presence of a very high biomass of diel vertical migrators that move between the surface waters at night and the suboxic waters during the day was a surprising finding from the US JGOFS sampling. Many of these animals spend the day at depths where the oxygen was less than 4.5 μM. For the January and March cruises combined, a mean of 15% ± 9 ($n = 9$) of the total biomass migrated into and out of the upper 100 m daily, 24% ± 18 of the large (> 2 mm) size fraction and 7% ± 6 of the small (< 2 mm) size fraction, based on wet weights of zooplankton from the MOCNESS

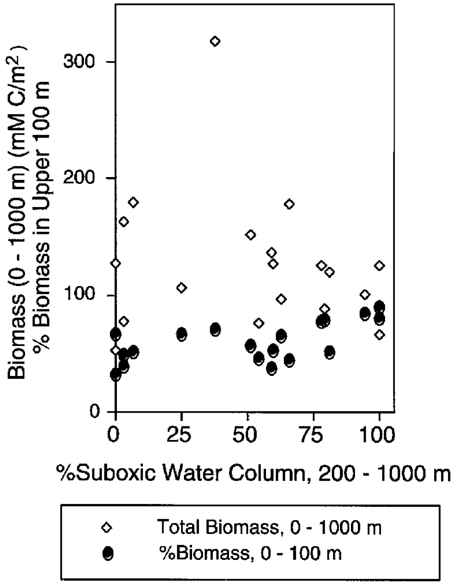

Fig. 12. Zooplankton water column biomass (0–1000 m) and the percent of that biomass in the upper 100 m at night relative to the percent of the deep water column (200–1000 m) that is suboxic (< 4.5 μM). The total biomass showed no statistical relationship to the amount of suboxic water but the percent of the biomass residing in the upper well-oxygenated surface layer was strongly correlated with the degree of suboxia. Data are from the nighttime dry weight MOCNESS samples from all 4 cruises and the oxygen sensor on the MOCNESS (Wishner et al., this volume).

tows (Wishner et al., 1998). Larger animals migrated deeper (to about 300–400 m) than the smaller zooplankton (to about 100–200 m), as indicated by the high day/night biomass ratios at these depths. Prominent diel vertical migrators in samples analyzed so far were euphausiids (especially *Euphausia diomedaea*) and several species of myctophid fish (Madin et al., pers. comm.). Possible effects on carbon and nitrogen cycling of this massive daily movement of biomass include the rapid transport of carbon below the mixed layer via daytime fecal pellet production and respiration, and the production of urea the depth by excretion.

The diel vertical migration was very prominent in the backscatter intensity measured by the acoustic Doppler current profiler (ADCP), and Fig. 13 clearly shows diel migration and movement into and out of the OMZ by organisms such as myctophid fish and euphausiids. Smith et al. (1998) did not see a similar migration of smaller species such as the copepods at station N7; in fact, this station showed the least diel migration by copepods of any station sampled. Daytime acoustic returns from depth were strong, and the dawn sinking and dusk rise of the fauna were obvious. However, at night the biomass remaining in the suboxic zone was so low that no ADCP signal was detectable at these depths. ADCP records also show at least two groups of plankton (used loosely), one that stayed in the upper mixed layer and another that

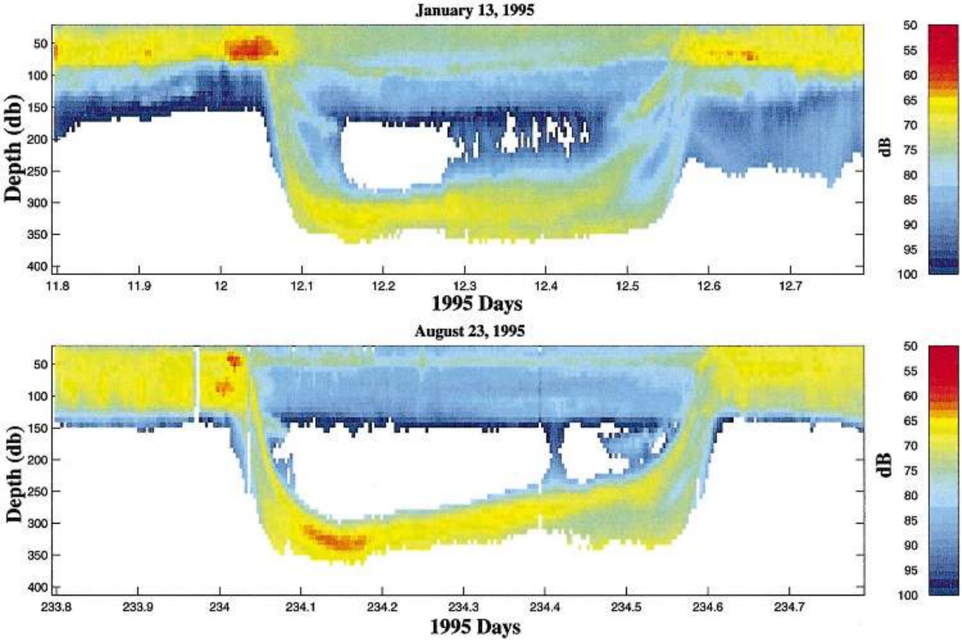

Fig. 13. Acoustic backscatter for 24 h around Station N7 for both TN043 and TN050. Diel vertical migration of the biological scattering layer is very prominent in the ADCP signal. Daytime acoustic returns from depth are strong, and the dawn sinking and dusk rise of the fauna are obvious. However at night, the remaining biomass in the suboxic zone was so low that no ADCP signal was detectable at these depths.

made the daily excursions. As the gaps between the mixed layer and the deep scattering layer indicate, the near surface and deep plankton populations are completely separate vertically, with few plankton found in between. This is also seen in the MOCNESS profiles (Smith et al., 1998; Wishner et al., 1998). The acoustic records also show that the vertical migration was composed of separate groups that began their migration at slightly different times.

An increase in zooplankton biomass and abundance typically occurred in the lower OMZ within the depth range of the oxygen gradient between 0.05 and 0.1 ml/l (2.3 and 4.5 μM) (where oxygen started to increase again) at locations with a strong and extensive OMZ (Fig. 11; Wishner et al., 1998). The depth of this subsurface biomass increase was usually located within the 400–500, 500–600 or 600–700 m depth interval, but occurred as shallow as 300–350 m and as deep as 1000–1100 m at different times and stations. The zooplankton sampling interval was usually 100 m at these depths, so it was not possible to resolve finer scale structure. From work here and elsewhere, this subsurface biomass feature is also known to be a location of relatively high zooplankton feeding rates and high potential food concentration measured as particulate organic carbon (Wishner et al., 1995). Detritivorous zooplankton from this zone in both the Eastern Tropical Pacific Ocean and the Arabian Sea had a variety of items in their guts, including intact phytoplankton cells (presumably from fast sinking material) and clumps of gram positive bacteria (possibly from the ingestion of bacterial aggregates that may be formed here) (Gowing and Wishner, 1992,1998). In the Arabian Sea at the depth of the subsurface biomass peak, a peak in aggregates was sometimes observed with a camera profiler (Walsh, pers. commn.), transmissometer profiles from the MOCNESS often showed a zone of increased scatter, a water sample containing bacterial aggregates was collected from a transmissometer scattering layer (G. Steward and D. Smith, pers. comm.), and peaks of protozoans, and crustacean nauplii, were sometimes present (Mowing, pers. comm.). The occurrence of high plankton and microbial biomass and a potentially short food chain suggest the possibility of intense utilization and biological alteration of suspended and sinking particles within a narrow midwater depth zone, defined physically by the oxygen gradients of the OMZ. Results from the US JGOFS sediment trap program also suggest that substantial changes in the quantity and quality of the sinking flux, possibly due to zooplankton processes, occurred within this depth zone (Arabian Sea Carbon Flux Group, 1998).

Various taxa in the subsurface biomass peak showed different distributional responses to the oxygen gradients, probably because of physiological differences in their ability to cope with low oxygen (Fig. 11). For example, the abundance peak of gelatinous taxa such as salps and doliolids was relatively shallow, where oxygen was still very low in the OMZ. Crustaceans (copepods, shrimp) and fish (*Cyclothone*) apparently required more oxygen and increased deeper in the water column where oxygen was somewhat higher.

The species in this subsurface biomass peak differed from those of the upper water column and from the diel vertical migrators. They were present day and night at depth, with no evidence in samples processed so far of diel vertical migration out of this zone. In contrast, the diel vertical migrators typically went down into the OMZ to about 100–400 m during the day and returned to the well oxygenated surface water at night to forage. A third group of organisms, the seasonal migrants such as the copepod *Calanoides carinatus*, spent a portion of their life cycle in the suboxic zone and in the more oxygenated water beneath it, mostly in a nonfeeding, diapausing stage. They rose into the surface waters in highest numbers during the Southwest monsoon, where they fed and reproduced (Smith et al., 1998). Thus, although the resident zooplankton biomass in the core of the OMZ was extremely low, there were several assemblages of organisms that inhabited parts of the suboxic zone, especially its upper and lower edges, at different times of the day or year.

The shapes of the zooplankton biomass profiles with depth corresponded to the shapes of the oxygen profiles (see Fig. 8 in Wishner et al., 1998). The degree of exclusion from the suboxic water and the distinctness of the deep subsurface biomass peak were the main contributors to the profile shape and were dependent on the vertical extent of the suboxic zone. The thickest layer of suboxic water occurred primarily at the offshore and central basin stations in the Arabian Sea (long stations S4, S7, S11, N7), especially during the three later cruises. At these stations, suboxic water was present over 51–100% of the 200–1000 m water column (Table 2 in Wishner et al., 1998), based on the continuous oxygen profiles from the MOCNESS sampling. Station S2, the most coastal station where MOCNESS sampling was carried out, and S15, the southern oligotrophic station, had higher oxygen levels in most of the water column most of the time (only 0–7% of the 200–1000 m water column was suboxic except in January), and organism distributions at these stations did not show distinct oxygen-related effects most of the year. However, in January 1995 during TN043, suboxic water was present nearshore at S2, and zooplankton biomass at depth was unusually low.

Zooplankton biomass profiles showed substantial geographic variability across the Arabian Sea, but comparatively little change between seasons at particular stations, except in the surface water and nearshore (Wishner et al., 1998). The consistency of the biomass profiles through time implies long-term stability in the structure and function of the mid-water ecosystem over a broad geographic region, and shows the strong influence of the OMZ on the biology of the deep Arabian Sea.

5. Summary

The data collected during the US JGOFS Arabian Sea Process Study represent the first consistent dataset covering an entire monsoonal cycle and, as such, should be ideal to look for seasonal variability in water properties. Overall, the conditions found in the suboxic portion of the water column in the Arabian Sea were not greatly different from what has been reported in the literature with respect to oxygen, nitrate and nitrite distributions (e.g., Naqvi, 1994), but we did not find the degree of seasonality that has been described in prior studies. This may reflect the difficulty of measuring oxygen at low concentrations, temporal variability, or both. Our measurements suggest modestly less well-developed oxygen deficient conditions during the SW monsoon, but few secondary nitrite maxima associated with oxygen values $> 5\ \mu$M were found. In general, the data do not suggest quite as dramatic a seasonal variability in secondary nitrite maxima and associated dissolved oxygen as observed by de Souza et al. (1996). In contrast, there is a definite seasonality in the primary nitrite maxima found near the bottom of the photic zone.

The concentration of particulate matter (and thus beam attenuation due to particles, c_p) generally decreases rapidly below the surface mixed layer (Gardner et al., 1995; Gundersen et al., 1998). In the Arabian Sea, however, there were regions where a secondary particle maximum, or intermediate nepheloid layer (INL), occurred between 150 and 350 m. The INL appears to be associated with secondary nitrate maxima. Seasonal variability in the intensity of the INL was also observed. During the SW monsoon and Spring Intermonsoon the maximum c_p signal was roughly 25% greater than during the two NE monsoons.

The presence of a very high biomass of diel vertical migrators that moved between the surface waters at night and the suboxic waters during the day was a surprising finding from the US JGOFS sampling. Many of these animals spent the day at depths where the oxygen was less the 0.1 ml/1 (or 4.5 μM). It is notable that the depth to which vertical migrators descend (150–400 m) is similar to the depths at which the intermediate nepheloid layers occur. Material transported and excreted by migrators may form a substrate for denitrifying processes. The vertical migration is composed of separate groups that begin their migration at slightly different times. Analysis of the MOCNESS data and correlation with the ADCP acoustic backscatter should allow us to differentiate these groups and determine if they are monospecific or collections of a small number of species. At the same time, zooplankton biomass profiles showed substantial geographic variability across the Arabian Sea, but offshore comparatively little change among seasons at particular stations. The area of upwelling nearer shore contains a zooplankton community that has an annual cycle which responds clearly and strongly to the SW monsoon. The consistency of the biomass profiles through time offshore implies long-term stability in the structure and function of the mid-water ecosystem over a broad geographic region and shows the strong influence of the OMZ on the biology of the deep Arabian Sea.

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