

Nitrate deficits by nitrification and denitrification processes in the Indian Ocean

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Abstract

The three-end-member mixing model of Li and Peng [Latitudinal change of remineralization ratios in the oceans and its implication for nutrient cycles. *Global Biogeochemical Cycles* 16, 1130–1145] was applied to the World Ocean Circulation Experiment (WOCE) data from Indian Ocean to obtain additional estimates on the remineralization ratios ($P/N_{org}-O_2$) of organic matter in the oxygenated regions. The results show systematic changes of the remineralization ratios with latitude and depth in the Indian Ocean. The average remineralization ratios for Indian warm water masses (potential temperature $\theta > \sim 10^\circ\text{C}$) are $P/N_{org}-O_2 = 1(15.6 \pm 0.7)(110 \pm 9)(159 \pm 8)$. These are comparable to the traditional Redfield ratios ($P/N_{org}-O_2 = 1/16/106/138$), and are in good agreement with Anderson's [On the hydrogen and oxygen content of marine phytoplankton. *Deep-Sea Research I* 42, 1675–1680.] values of $P/N_{org}-O_2 = 1/16/106/150$ within the given uncertainties. Separation of nitrate deficits resulting from aerobic partial nitrification (dN) and anaerobic denitrification (dN'') processes using empirical equations is shown to be useful and consistent with other observations. The dN maximum coincides with the phosphate and nitrate maximums, lies within the oxycline below the oxygen minimum zone, and is in contact with the continental slope sediments. The dN'' maximum lies within the oxygen minimum zone with $O_2 < \sim 2 \mu\text{mol/kg}$, is in contact with shelf or upper slope sediments, and is always associated with a secondary nitrite maximum in the water column. The spatial extent of dN is much larger than that of dN'' . The low N/P remineralization ratio (< 15) for deep waters ($\theta < \sim 10^\circ\text{C}$) and the dN maximum in the lower oxycline can be best explained by the partial conversion of organic nitrogen into N_2 , N_2O , and NO by yet unidentified bacteria during oxidation of organic matter. These bacteria may have evolved in a low oxygen and high nitrate environment to utilize both oxygen and nitrate as terminal electron acceptors during oxidation of organic matter (i.e. the partial nitrification hypothesis). Direct proof is urgently needed.

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Keywords: Remineralization ratios; Nitrification; Partial nitrification; Denitrification; Anammox; Nitrate deficit; Indian Ocean

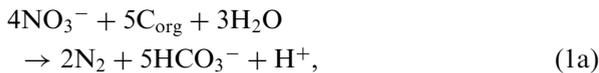
1. Introduction

Nitrate losses by the denitrification process in the northern Arabian Sea and in the eastern tropical Pacific Ocean at intermediate depths (100–800 m) with zero oxygen (anoxic) to near zero oxygen

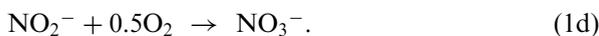
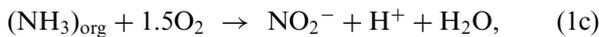
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(suboxic) concentrations are well documented (Naqvi et al., 1982, 1990; Naqvi and Sen Gupta, 1985; Codispoti and Christensen, 1985; Ward and Zafriou, 1988; Ward et al., 1989; Mantoura et al., 1993). The denitrification process is suppressed when the concentration of oxygen in the eastern tropical North Pacific water is higher than about $2\ \mu\text{mol/kg}$ (Devol, 1978). Therefore, we set the upper limit of the term “suboxic” at oxygen concentration about $2\ \mu\text{mol/kg}$ in this paper. In the oxygen minimum zone with $\text{O}_2 < \sim 2\ \mu\text{mol/kg}$, some nitrate is actively reduced to N_2 by denitrifying bacteria (Codispoti and Christensen, 1985; Ward et al., 1989) through reactions such as



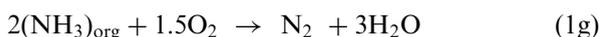
where C_{org} and $(\text{NH}_3)_{\text{org}}$ are carbon and nitrogen in organic matter. For clarity, the term “denitrification” is strictly applied only to the reduction/oxidation processes occurring in an oxygen minimum zone with $\text{O}_2 < \sim 2\ \mu\text{mol/kg}$, and we refer to this oxygen minimum zone as the denitrification zone throughout this paper. Below and above the denitrification zone are oxygen gradient layers (oxyclines), where the abundance and activity of nitrifying bacteria (including ammonium oxidizers and nitrite oxidizers) are highest (Ward et al., 1989). Furthermore, nitrifying bacteria were also shown to be present throughout the denitrification zone (Ward et al., 1989). In oxyclines, most of the organic nitrogen is oxidized into nitrite and nitrate (i.e. nitrification processes) through net reactions such as



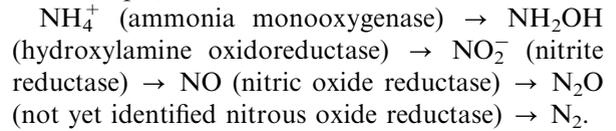
However, some is oxidized only up to N_2O and NO (Codispoti and Christensen, 1985; Ward and Zafriou, 1988; Ward et al., 1989; Naqvi and Noronha, 1991) through net reactions such as



Thermodynamically, the production of N_2 by yet unidentified bacteria in the same oxyclines by a net reaction such as

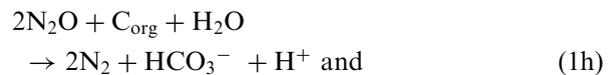


is a real possibility, though a direct proof is still lacking. Schmidt et al. (2004) did show that a wild type of *Nitrosomonas europaea* bacteria in chemostat cell cultures can produce nitrogen gases (N_2 , NO , and N_2O) during aerobic oxidation of ammonia, using genes encoding reduction enzymes such as nitrite reductase, nitric oxide reductase etc. For example,



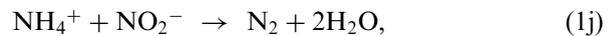
The same species also can produce N_2 with addition of NO_2 as oxidizing agent in the reactor during anoxic oxidation of ammonia (Schmidt et al., 2004).

The N_2O and NO produced in the oxyclines may diffuse into the denitrification zone and be reduced to N_2 by the following reactions



forming nitrification–denitrification coupled pathways to produce N_2 (Codispoti and Christensen, 1985).

Another important reaction to produce N_2 is the anaerobic ammonia oxidation (anammox) reaction



mediated by the anammox bacteria belonging to the order Planctomycetales (Strous et al., 1999; Thamdrup and Dalsgaard, 2002; Dalsgaard and Thamdrup, 2002; Kuypers et al., 2003, 2005). Hydroxylamine (NH_2OH) and hydrazine (N_2H_4) have been shown to be involved in the anammox reaction as intermediate species (Van de Graaf et al., 1997).

Nielsen et al. (2005) demonstrated that aerobic and anaerobic ammonia-oxidizing bacteria act closely to remove ammonia in an oxygen-limited ($\sim 5\ \mu\text{M}\text{O}_2$) CANON (acronym of Completely Autotrophic Nitrogen removal Over Nitrite) reactor. Aerobic ammonia-oxidizing bacteria are active in the thin surface layer of organic particles in the CANON reactor and oxidize ammonia into nitrite. Nitrite is then diffused into the anoxic interior of the particles where anammox bacteria convert nitrite and ammonia into N_2 . Marine snow and fecal pellet particles suspended in a low oxygen water column (such as oxyclines) may prove to be the ideal sites for the coupling of aerobic ammonia oxidation and

anammox reactions. However, anaerobic conditions were never observed within the marine snow and fecal pellets suspended in high oxygen water column, using O_2 microelectrode (Alldredge and Cohen, 1987). Only one large fecal pellet (6.2 mm long) showed the complete depletion of O_2 . The nitrogen isotopic data of N_2O from the western North Pacific (Yamagishi et al., 2005) may suggest partial oxidation of organic nitrogen to nitrite first, then, reduction of nitrite to N_2O (as well as to NO and N_2 ; Schmidt et al., 2004).

Gruber and Sarmiento (1997) introduced a new parameter N^* that is defined as

$$N^* = 0.87[N - \bar{N}], \quad (2a)$$

where $\bar{N} = 16(P - 0.181)$, representing a global mean relationship between nitrate + nitrite (N) and orthophosphate (P) concentrations based on all GEOSECS data. Later, Deutsch et al. (2001) redefined N^* to

$$N^* = N - \bar{N}. \quad (2b)$$

Therefore, N^* is a measure of the deviation of the observed N from \bar{N} for a given P . They interpreted a negative N^* as mostly caused by the loss of nitrate through the denitrification process, and a positive N^* by the gain of nitrate through N_2 fixation by N_2 -fixing bacteria. By this interpretation, the loss of nitrate by the denitrification process could be widespread even in the oxic regions of the oceans (Gruber and Sarmiento, 1997).

Codispoti et al. (2001) estimated the excess N_2 in the water column of the Arabian Sea, using the Ar/ N_2 ratio in the water column and in the air. They found that the excess N_2 is substantially greater than the N_2 produced by the denitrification process. The implication is that there must be some other N_2 -producing mechanisms in the water column.

Li and Peng (2002) introduced a new three-end-member mixing model to estimate the remineralization ratios of organic matter in the oxic water column. They showed that the remineralization ratios ($P/N/C_{org}-O_2$) of organic matter in the oxic deep ocean ($\theta < 10-12^\circ C$) change systematically within one ocean and from one ocean to another. In particular, the remineralization ratios for the deep equatorial Indian Ocean [$P/N/C_{org}-O_2 = 1(10 \pm 1)(94 \pm 5)(130 \pm 7)$] are quite different from those for the Southern Indian Ocean [$P/N/C_{org}-O_2 = 1(15 \pm 1)(83 \pm 2)(134 \pm 9)$]. The apparent low N/P remineralization ratio for the oxygenated deep equatorial Indian Ocean may

indicate that most of the organic nitrogen was oxidized into nitrate but some into NO, N_2O and N_2 by yet unidentified bacteria during oxidation of organic matter (Li and Peng, 2002). This interpretation is called the partial nitrification hypothesis throughout this paper. As will be shown later, the partial nitrification may occur in the oxyclines around the denitrification zone, the steep oxygen gradients within marine-snow particles and fecal pellets suspended in a low oxygen (but still oxic) water column, and within the bottom sediments if the pore water or overlying water is low in oxygen and enriched in nitrate.

Naqvi and Noronha (1991) confirmed the production of N_2O in the oxyclines around the secondary nitrite maximum zone (corresponding to the denitrification zone) in the Arabian Sea. Furthermore, the observed strong correlation between apparent oxygen utilization (AOU) and ΔN_2O (the N_2O level above atmospheric equilibrium) in the oxyclines supports the dominant role of the partial nitrification process for producing N_2O (probably NO and N_2 as well). Nevison et al. (2003) also reached the same conclusion, based on the global distribution pattern of N_2O and the positive correlation between AOU and ΔN_2O .

The purposes of the present study are threefold: First, to reconfirm the variability of remineralization ratios in the Indian Ocean by applying the three-end-member mixing model (Li and Peng, 2002) to the World Ocean Circulation Experiment (WOCE) data along the E–W sections shown in Fig. 1. Second, to introduce an empirical model to distinguish the nitrate deficit caused either by aerobic partial nitrification (dN) or by anaerobic denitrification (dN'') processes and elucidate their relative importance. Finally, to discuss the spatial distribution patterns of dN and dN'' in the Indian Ocean and their relationship with those for O_2 and nitrite (NO_2^-) concentrations. Similar results from the Pacific Ocean will be presented in a separate paper (Y.H. Li, L. Menviel, and T.H. Peng, Nitrate deficits by nitrification and denitrification processes in the Pacific Ocean, in preparation).

2. Water mass end members and remineralization ratios

Many useful section plots of potential temperature (θ), salinity (S), oxygen (O_2), nutrients (phosphate, nitrate, and silica), dissolved inorganic carbon (DIC), alkalinity (Alk), and chlorinated

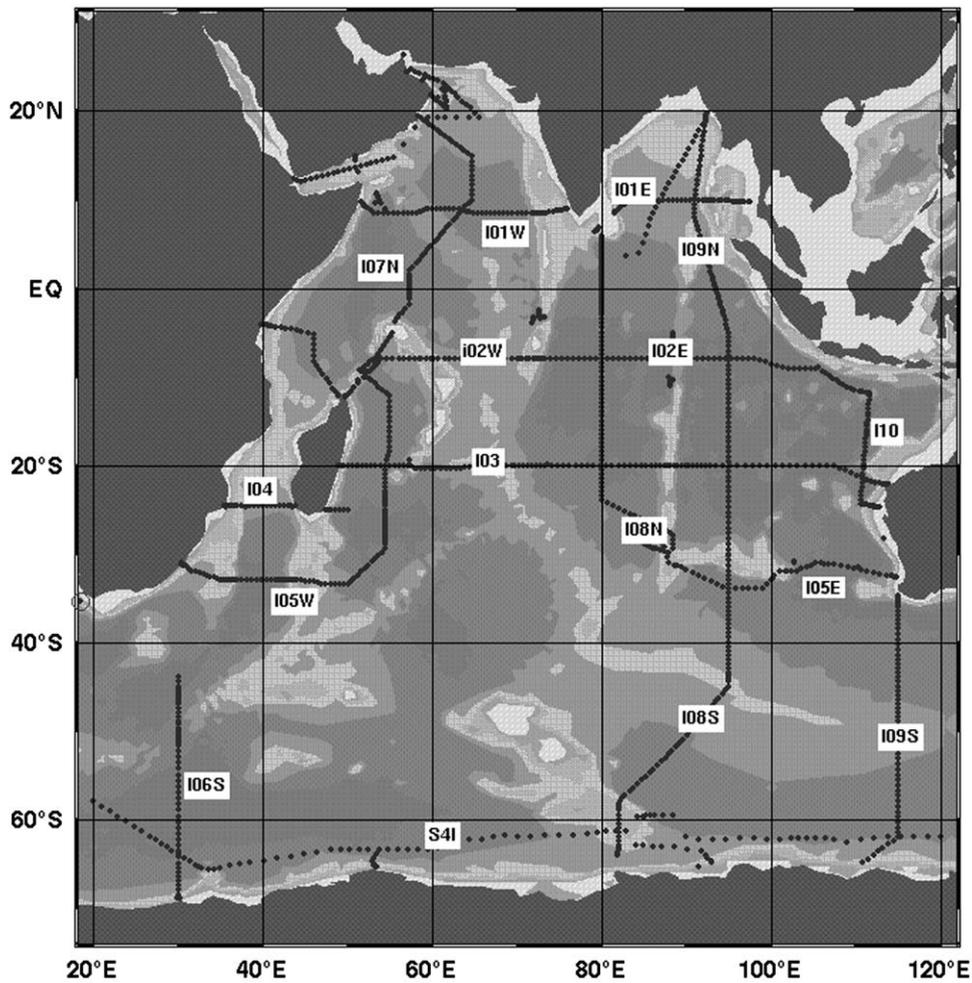


Fig. 1. WOCE cruise tracks in the Indian Oceans.

fluoro-carbon (CFC-11) along the WOCE cruise tracks can be found in the eWOCE Gallery as established by Schlitzer (2000; <http://www.awi-bremerhaven.de/GEO/eWOCE/index.html>). Additional section plots for the Indian Ocean based on GEOSECS data are given by Spencer et al. (1982). Those plots are helpful in identifying water masses and their spatial extent, and the remineralization sites of organic matter, etc. The emphasis here is to first identify the water mass end members along the E–W sections (WOCE cruise tracks i01 to i05 and s4i in Fig. 1) for the three-end member mixing model of Li and Peng (2002).

From Figs. 2 to 4, one can easily identify the following end members of water masses. I = Antarctic Bottom Water, II = Circumpolar Deep Water, III = Antarctic Intermediate Water, IV = Sub-Antarctic Oxygen Maximum Water,

V = South Indian Central Water, III* = Equatorial Indian Phosphate Maximum Water, IV*e and IV*w = eastern and western Equatorial Indian Central Water, V* = Red Sea Water, and various surface waters. The asterisks indicate the end members formed north of the equator. Data points between two dotted horizontal lines (i.e. the interval between two given potential temperatures, θ) in Figs. 2a–d can be produced by mixing the three appropriate end members shown in those figures. Therefore those data within a given θ interval can be fitted by the three-end-member mixing model of Li and Peng (2002) to obtain remineralization ratios. This model essentially involves a multiple-variable linear regression of hydrographic data, including θ , salinity, O_2 , and one of nutrients (nitrate, phosphate, and DA [= DIC–Alk/2]). The advantage of this model is that it requires no knowledge of end

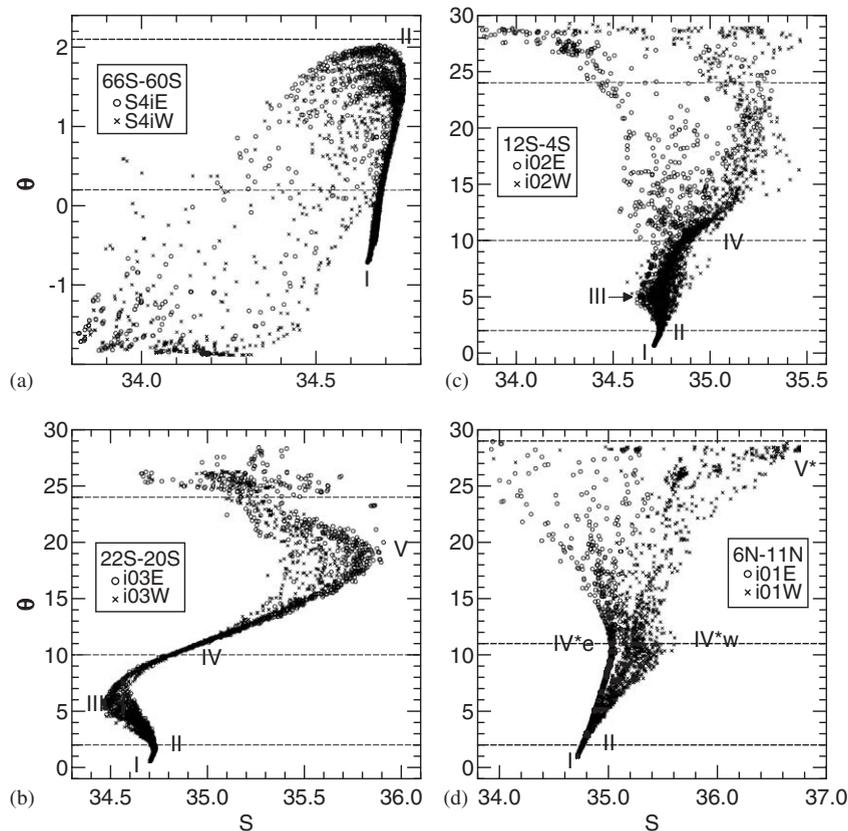


Fig. 2. Salinity (S) versus potential temperature (θ) for data from (a) cruise s4i, (b) cruise i03, (c) cruise i02, and (d) cruise i01. Roman numerals represent various water mass end members: I = Antarctic Bottom Water, II = Circumpolar Deep Water, III = Antarctic Intermediate Water, IV = Sub-Antarctic Oxygen Maximum Water, V = South Indian Central Water, III* = Equatorial Indian Phosphate Maximum Water, IV*e and IV*w = eastern and western Equatorial Indian Central Water, respectively, V* = Red Sea Water. Sections E and W for each cruise are roughly separated along the Mid-Indian Ridge.

member values for those variables. Model results are summarized in Table 1. In Fig. 2d for cruise i01, the data points for θ between 2 and 10 $^{\circ}\text{C}$ can be produced by mixing end members II, IV*e, and IV*w, but there is an additional end member III* in the same θ interval as shown in Fig. 4d. Thus, those data cannot be fitted to our three-end-member mixing model. Furthermore, the data points above $\theta = 11$ $^{\circ}\text{C}$ for the cruise i01w (Fig. 2d) need four-end-member mixing and show some effect of the denitrification (to be discussed later), so those are also not suitable for the model.

The newly calculated remineralization ratios for deep water along E–W sections are in good agreement with the earlier estimates along N–S sections (Table 1; Li and Peng, 2002); they confirm that the N/P ratio decreases from 15 ± 1 in the Southern Oceans to 10 ± 1 in the deep equatorial

Indian Ocean. As shown in Figs. 3a–c, those deep waters are all high in dissolved O_2 concentrations ($> 50 \mu\text{mol}/\text{kg}$); thus, the decrease of the N/P ratio is difficult to explain by the loss of nitrate into N_2 through the denitrification process. In short, the variation of dissolved O_2 , P, N and DA (= $\text{DIC} - \text{Alk}/2$; Li and Peng, 2002) in any properly chosen oxic region can be best explained by the water mass mixing and the in situ partial nitrification process.

The interesting results are the remineralization ratios obtained for the shallower warm water masses ($\theta > \sim 10$ $^{\circ}\text{C}$) above the Sub-Antarctic Oxygen Maximum Water (IV), including South Indian Central Water (V), eastern Equatorial Indian Central Water (IV*e), and various surface waters. The average remineralization ratios for the Indian warm water masses are $\text{P}/\text{N}/\text{C}_{\text{org}}/\text{O}_2 = 1/(15.6 \pm 0.7)/(110 \pm 9)/(159 \pm 8)$ (from bold values

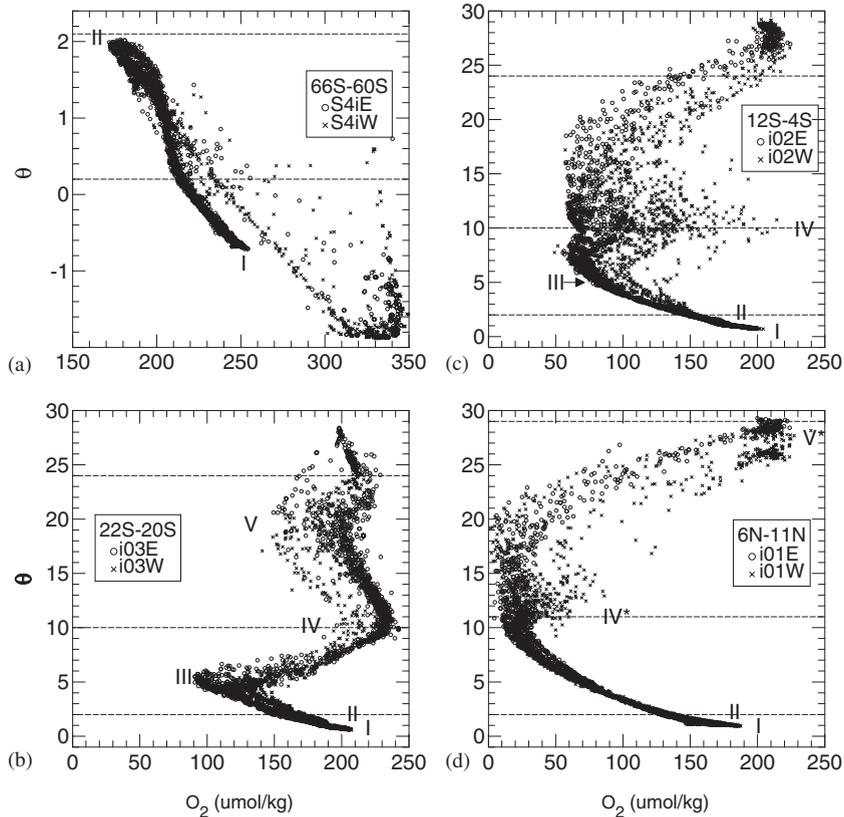
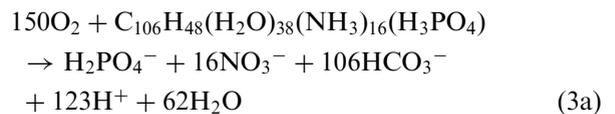


Fig. 3. Oxygen concentration (O_2 ; $\mu\text{mol/kg}$) versus θ for the same transects as in Fig. 2.

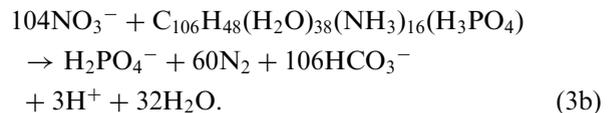
in Table 1), which are distinctly different from those for the deep Indian Ocean (Table 1). Using different approaches, Shaffer (1996) and Shaffer et al. (1999) also reached the same conclusion that remineralization ratios change with depth. The remineralization ratios for the warm waters are comparable to the traditional Redfield ratios ($P/N/C_{\text{org}} \sim O_2 = 1/16/106/138$), and in good agreement with that suggested by Anderson (1995; $P/N/C_{\text{org}} \sim O_2 = 1/16/106/150$) within the given uncertainties. The low $-O_2/P$ ratio of 138 for the traditional Redfield ratios results from Redfield's (1958) unrealistic assumption that all organic carbon in plankton exists purely as carbohydrates, represented in the idealized chemical formula $(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}(\text{H}_3\text{PO}_4)$ for marine plankton. It is time to discontinue the usage of this formula for marine plankton but not Redfield's concept.

One can rewrite Anderson's formula for marine phytoplankton ($\text{C}_{106}\text{H}_{175}\text{O}_{42}\text{N}_{16}\text{P}$) into $\text{C}_{106}\text{H}_{48}(\text{H}_2\text{O})_{38}(\text{NH}_3)_{16}(\text{H}_3\text{PO}_4)$ according to the procedure given by Li and Peng (2002). Its oxidation by

oxygen (nitrification) through nitrifying bacteria can be written as



and oxidation by nitrate (denitrification) through denitrifying bacteria under anoxic or suboxic condition as



In short, nitrifying bacteria use oxygen and denitrifying bacteria use nitrate as terminal electron acceptors during oxidation of organic matter. In contrast, some yet unidentified bacteria (probably similar to *Nitrosomonas europaea*; Schmidt et al., 2004) may have evolved in oxyclines, where the concentration of oxygen is relatively low and nitrate high, and are able to utilize both oxygen and nitrate

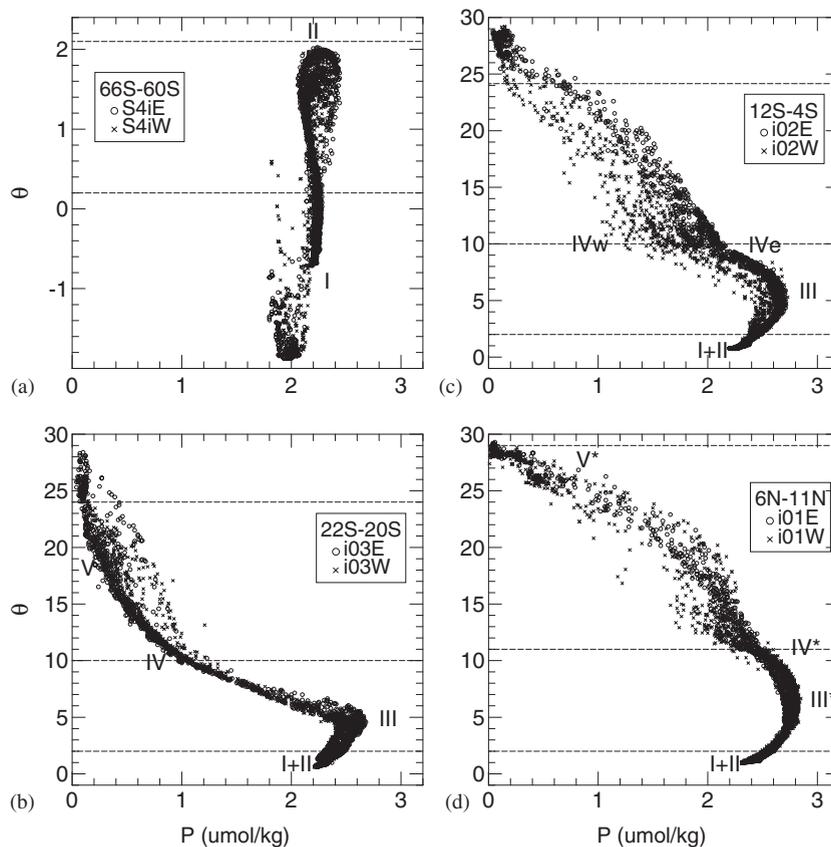


Fig. 4. Orthophosphate concentration (P ; $\mu\text{mol/kg}$) versus θ for the same transects as in Fig. 2, with end member III* representing the Equatorial Indian Phosphate maximum water.

as terminal electron acceptors. The coupling of aerobic and anaerobic ammonia oxidizing bacteria (Nielsen et al., 2005) in marine snow and fecal pellets suspended in low oxygen water column (such as in oxyclines) may provide additional mechanisms for the partial nitrification.

As schematically shown in Fig. 5, the cycling of nitrogen in the oceans also involves other nitrogen species with different oxidation states during nitrification, denitrification, and anammox processes; all are facilitated by different bacteria species with genes encoding specific enzymes (Amend and Shock, 2001). One important difference between reactions (3a) and (3b) is that nitrification produces many hydrogen ions but denitrification does not. Also reaction (3a) reduces Alk by 16 units and reaction (3b) adds Alk by 104 units for every increment of one P unit in the water column.

In summary, our present and earlier studies (Li and Peng, 2002) have amply demonstrated the variability of remineralization ratios from region

to region and from the surface to deep waters. One should be cautious about the earlier assumption that remineralization ratios are constant throughout the whole ocean (Broecker et al., 1985; Anderson and Sarmiento, 1994).

3. Nitrate deficits by partial nitrification (dN) and denitrification (dN'')

As shown in Figs. 6a–d (P versus N), the data points from the shallow water of cruise s4i and the warm water masses ($\theta > \sim 10^\circ\text{C}$) of cruises i03, i02, and i01 all fall on straight lines with a slope of about 16.5 ± 0.5 . Therefore, both P and N are controlled by the complete nitrification of organic nitrogen without net production of NO , N_2O and N_2 during oxidation of organic matter in the oxygenated shallow water column. One may write the relationship between P and N as

$$N_a = m(P - P_0), \quad (4a)$$

Table 1
Remineralization ratios based on the WOCE data from the Indian Ocean

Transect	Latitude	Long. (E)	Stations	θ (°C)	r_p	r_n	r_p/r_n	r_c	r_p/r_c
Redfield					138	8.6	16	1.30	106
E–W (present study)									
i01E	10N-6N	80-98	962-1014	11-29	156±4	10.6±0.2	14.7±0.5	1.35±0.04	115±4
i02E	8S-9S	71-106	1077-1154	2-10	115±2	10.3±0.1	11.2±0.2	1.43±0.04	80±2
i02W	4S-12S	40-71	1155-1244	2-10	119±1	9.6±0.1	12.4±0.2	1.58±0.03	75±1
i02EW	4S-12S	40-106	1077-1244	10-24	146±2	9.0±0.1	16.2±0.3	1.49±0.02	99±2
i03E	20S-22S	66-114	444-522	2-10	131±1	10.7±0.1	12.2±0.1	1.59±0.03	82±1
i03W	20S-22S	53-66	523-573	2-10	126±2	10.0±0.1	12.6±0.2	1.55±0.03	81±2
i03EW	20S-22S	53-114	444-573	10-24	168±7	10.1±0.6	16.6±1.2	1.54±0.05	109±8
i04W	25S	35-44	585-610	2-12	112±1	9.1±0.1	12.3±0.2	1.49±0.02	75±1
				12-20	158±2	10.4±0.1	15.2±0.2	1.54±0.03	103±2
i05W	31S-34S	30-50	611-669	2-10	117±1	9.4±0.1	12.4±0.2	1.47±0.02	80±1
				10-20	169±3	11.0±0.2	15.4±0.4	1.35±0.06	125±3
i05E	30S-33S	88-115	395-442	2-8	127±2	10.4±0.1	12.2±0.2	1.59±0.10	80±1
S4iE	60S-62S	84-120	65-108	0.2-2.1	118±7	8.3±0.3	14.2±1.0	1.38±0.13	86±6
S4iW	61S-66S	34-83	20-64	0.2-2.1	122±5	8.6±0.3	14.2±0.8	1.39±0.12	88±5
N–S (Li and Peng, 2002)									
i09N	19.6N-2.7N		213-277	0.8-11	131±1	13.0±0.2	10.1±0.2	1.37±0.04	95±2
i09N	2N-18.5S		172-212	0.8-8	142±1	13.4±0.2	10.6±0.2	1.39±0.04	102±2
i09N	19S-31S		148-171	2-10	134±1	10.5±0.1	12.8±0.2	1.57±0.03	86±1
i08S	30.3S-51S		4-49	2-11	133±3	9.5±0.3	14.0±0.5	1.66±0.08	80±3
i08S	51.4S-63.3S		50-84	0.2-2	130±3	8.5±0.2	15.3±0.5	1.52±0.07	85±3

Note: $r_p = -O_2/P$; $r_n = -O_2/N$; $r_p/r_n = N/P$; $r_c = -O_2/C_{org}$; $r_p/r_c = C_{org}/P$.
 Bold numbers are for warm water masses with $\theta > 10\text{--}12^\circ\text{C}$.

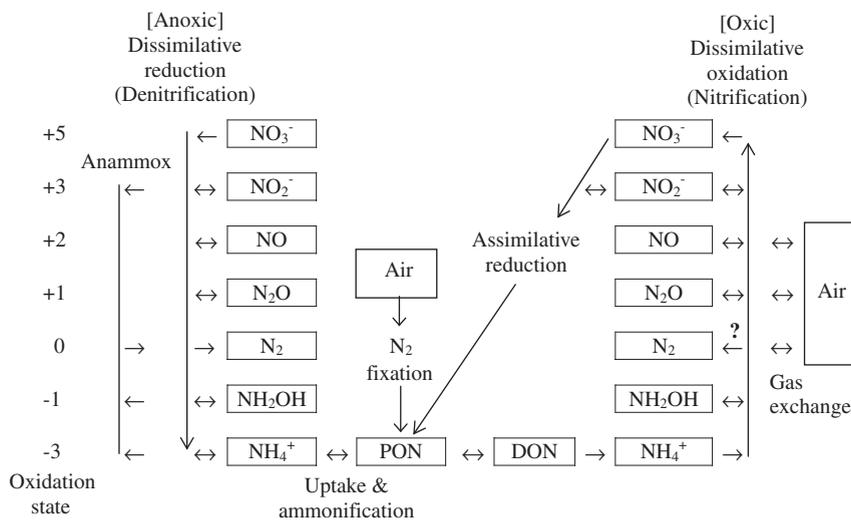


Fig. 5. Schematic representation of the nitrogen cycle in the ocean. Dissimilative processes do not involve cellular incorporation, and are mediated by bacteria at cell–water interface. Anammox is the anaerobic ammonia oxidation.

where m = slope, P_o = intercept of P at $N = 0$, and N_a represents the expected concentration of N from the right hand side of Eq. (4a) for a complete nitrification. The m and P_o can be obtained by the linear least-square fitting of the shallow water data

with $N \geq \sim 1 \mu\text{mol/kg}$ as well as $P \leq \sim 1.6 \mu\text{mol/kg}$ in a chosen region. In case of $P < P_o$ for some shallow water (Figs. 6b–d), N_a becomes negative according to Eq. (4a). A negative N_a only means zero concentrations of nitrate and nitrite, and a potential

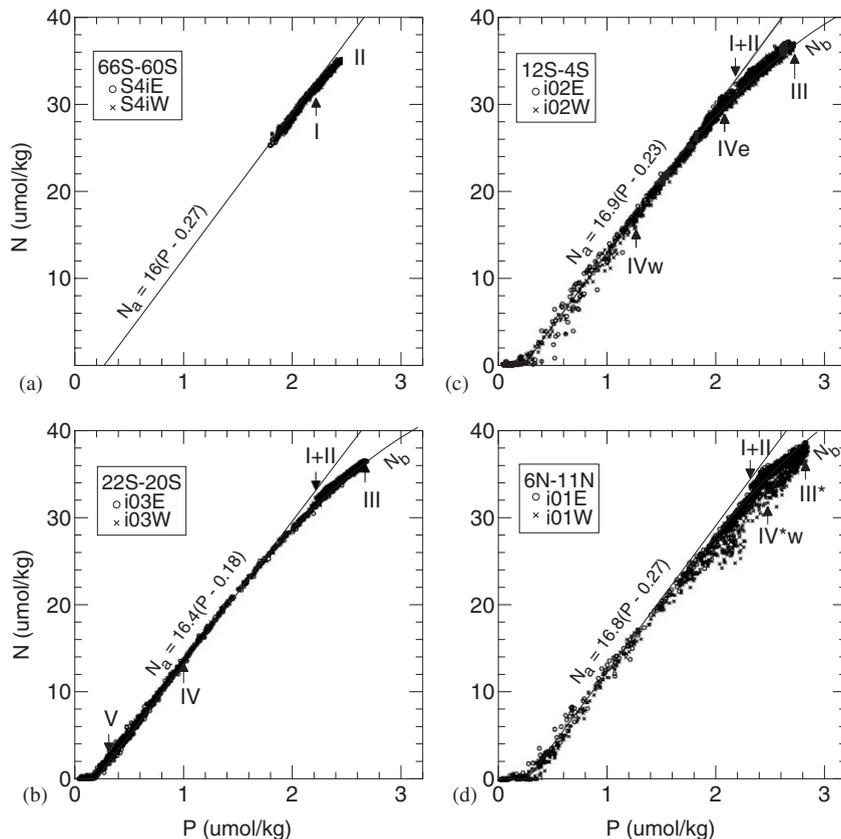


Fig. 6. P versus N ($=$ nitrate+nitrite; $\mu\text{mol}/\text{kg}$) versus θ for the same transects as in Fig. 2. See the text and Eq. (3a)–(3b) for the explanation of the lines N_a and N_b .

for microbial N_2 fixation, but does not indicate any actual N_2 fixation and its intensity.

In contrast, the data points for the Antarctic Bottom Water (I), Circumpolar Deep Water (II), and Antarctic Intermediate Water (III) from cruises i03 and i02, which have the highest P and N concentrations (Figs. 4b and c), all fall below the straight line N_a in Figs. 6b and c. The Antarctic Intermediate Water (III) mixes smoothly with the deeper waters (end members I and II) and with the shallower Sub-Antarctic Oxygen Maximum Water (IV). The N/P slope of much less than 16.5 ± 0.5 for the Antarctic Intermediate Water (III) again can be best explained by the partial nitrification in oxygenated water columns as discussed earlier. The P – N relationship resulted from in situ oxidation of organic matter and the mixing of end members III and IV can be represented by an empirical cubic equation such as

$$N_b = c_0 + c_1P + c_2P^2 + c_3P^3, \quad (4b)$$

where c_i are constants, and N_b represents the expected concentration of N from the right hand side of Eq. (4b) during a partial nitrification (with net N_2 , N_2O and NO production). The c_i can be obtained by the least-square fitting of the data points with depths equal to and shallower than those of the Antarctic Intermediate Water (III) ($\theta > \sim 5$ – 6°C) and $N \geq \sim 1 \mu\text{mol}/\text{kg}$, using the Statistical Package for the Social Sciences (SPSS) curve fitting program. N_b is always equal to or less than N_a .

For a given P , when $N_a > N > N_b$, we define the nitrate deficit by the partial nitrification (dN) as

$$dN = N_a - N. \quad (4c)$$

The Equatorial Indian Phosphate Maximum Water (III*) data also fall below the N_a line (Fig. 6d) and form a smooth mixing line N_b with the end members I+II and the eastern Equatorial Indian Central Water (IV*e). However, the samples shallower than the end member III* in the western Indian Ocean,

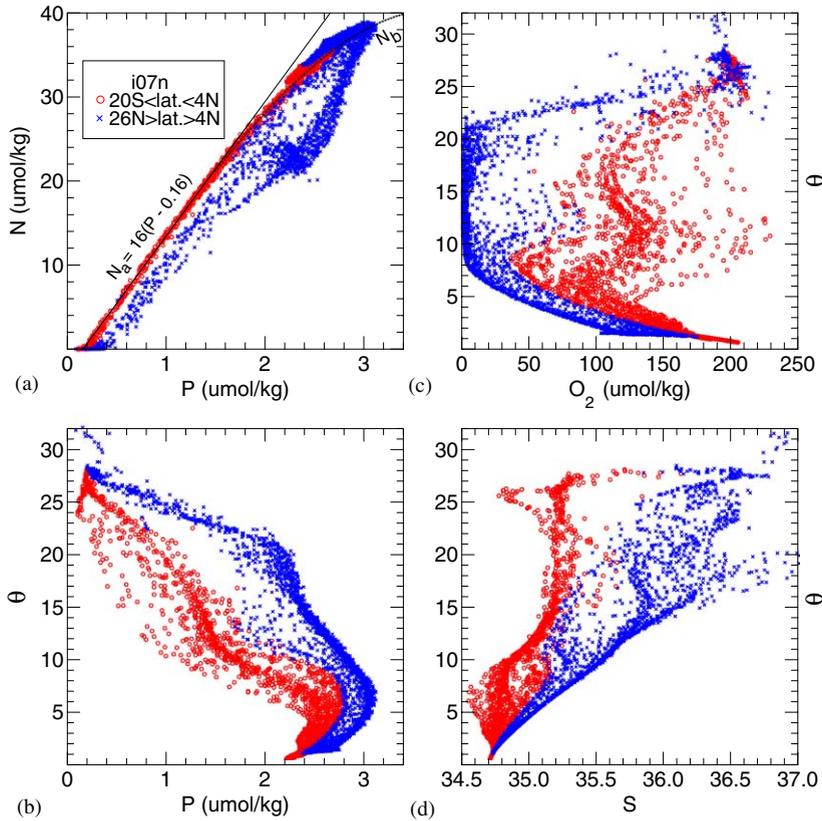


Fig. 7. (a) P vs. N , (b) P vs. θ , (c) O_2 vs. θ , and (d) S vs. θ for the cruise i07n data. N_a and N_b are Eqs. (5a) and (5b) in the text.

including the western Equatorial Indian Central Water (IV^*w), all fall below the mixing line N_b (crosses in Fig. 6d), and have low O_2 concentration but not below $2 \mu\text{mol/kg}$ (Fig. 3d). Those samples represent the nitrate deficit by denitrification, mixed in from the main denitrification zone of the Arabian Sea (see the discussion later).

For a given P , when $N < N_b$, the nitrate deficit can be caused by both partial nitrification and denitrification. We define here the nitrate deficit by partial nitrification (dN) operationally as

$$dN = N_a - N_b \quad (4d)$$

and the nitrate deficit by denitrification (dN'') as

$$dN'' = N_b - N. \quad (4e)$$

In practice, N_a is almost equal to N_b for samples with P less than $1.6\text{--}1.8 \mu\text{mol/kg}$ (Figs. 6b–d). Therefore, dN are set to zero for all shallow water samples with $P \leq \sim 1.6 \mu\text{mol/kg}$ to eliminate unnecessary data noise.

The internal consistency and usefulness of the new parameters dN and dN'' are demonstrated by

the following example for the cruise i07n, which traverses the Arabian Sea from 27°N to 18°S (Fig. 1). As shown in Fig. 7a, we first obtained the following N_a and N_b equations for the cruise i07n by curve fittings:

$$N_a = 16(P - 0.16) \quad (5a)$$

and

$$N_b = -3.223 + 16.772P + 0.374P^2 + 0.465P^3. \quad (5b)$$

The data points between 4°N and 26°N (crosses in Fig. 7a) and with depth shallower than the phosphate maximum (Fig. 7b) all fall below the mixing line N_b in Fig. 7a. Those data points also encompass the oxygen minimum zone with $< \sim 2 \mu\text{mol/kg}$ (Fig. 7c), confirming the dominance of the denitrification process. In contrast, the data points at and deeper than the phosphate maximum all fall between the N_a and N_b lines and encompass the oxycline below the oxygen minimum zone (Fig. 7c), confirming the dominance of the partial nitrification process.

4. Spatial distributions of dN and dN''

Substituting Eqs. (5a)–(5b) into Eqs. (4d)–(4e), the dN and dN'' values for each given pair of P and N in the cruise i07n were calculated. From the spatial distribution patterns of dN and O_2 concentrations (Fig. 8; all in units of $\mu\text{mol}/\text{kg}$), it is evident that the dN maximum zone ($\geq 7 \mu\text{mol}/\text{kg}$) lies within the oxycline just below the oxygen minimum zone from 26°N down to the equator. South of the equator, the dN maximum tends to coincide with the oxygen minimum. The dN maximum in the lower oxycline is on the order of $8 \mu\text{mol}/\text{kg}$ (Fig. 8), while the N_2O maximum in the oxyclines of the Indian and the equatorial eastern Pacific Oceans is only on the order of $0.08 \mu\text{mol}/\text{kg}$ (Nevison et al., 2003). Allowing some diffusive or mixing loss of N_2O , most of dN must be caused by conversion of $(\text{NH}_3)_{\text{org}}$ into N_2 to keep the nitrogen mass balance. The dN maximum zone ($\geq 7 \mu\text{mol}/\text{kg}$) is in contact with the continental slope sediments at depths between 1000 and 1700 m (Fig. 8), indicating some nitrate deficit sources from sediments probably by

all N_2 -producing processes including partial nitrification, denitrification and anammox. It is unlikely that nitrate deficit sources from sediments can explain the whole integrated dN throughout cruise i07n (Fig. 8). Since dN maximum zone coincides with the P or N maximum zone (compare Figs. 7b and 10a) and lies within the lower oxycline, one can envision that some yet unidentified bacteria have evolved there to utilize both oxygen and nitrate to oxidize organic matter. Identification of these bacteria and elucidation of the detailed pathways of the partial nitrification in the oxyclines are urgently needed.

The spatial distributions of dN'' and nitrite as shown in Fig. 9 are confined within the area defined by the oxygen contour line of $10 \mu\text{mol}/\text{kg}$ (Fig. 8). The dN'' maximum ($10 \mu\text{mol}/\text{kg}$) is in contact with the upper continental slope sediments at depths between 300 and 500 m (Fig. 9), indicating some denitrification inputs from the sediments as well. There is no easy way to distinguish the relative magnitude of the dN'' inputs from sediments and from in situ water column production. Obviously,

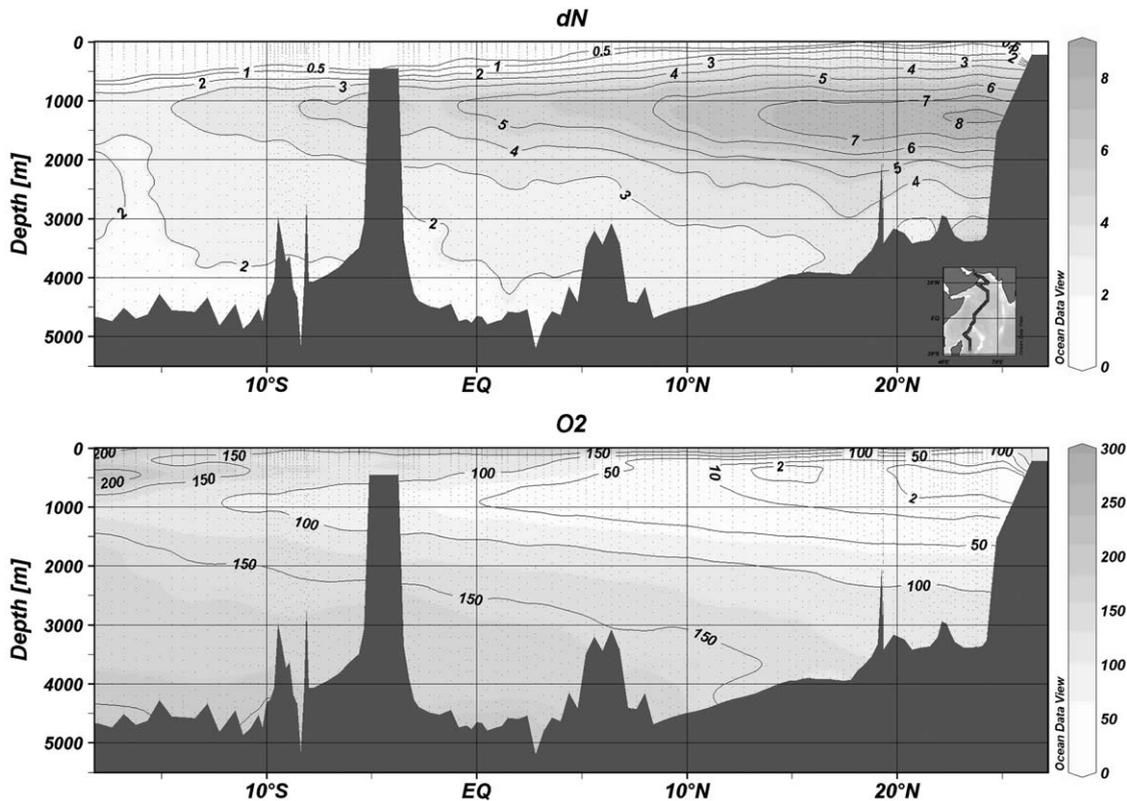


Fig. 8. dN (nitrate deficit by partial nitrification; $\mu\text{mol}/\text{kg}$) and O_2 contours in a latitude–depth space for the cruise i07n data.

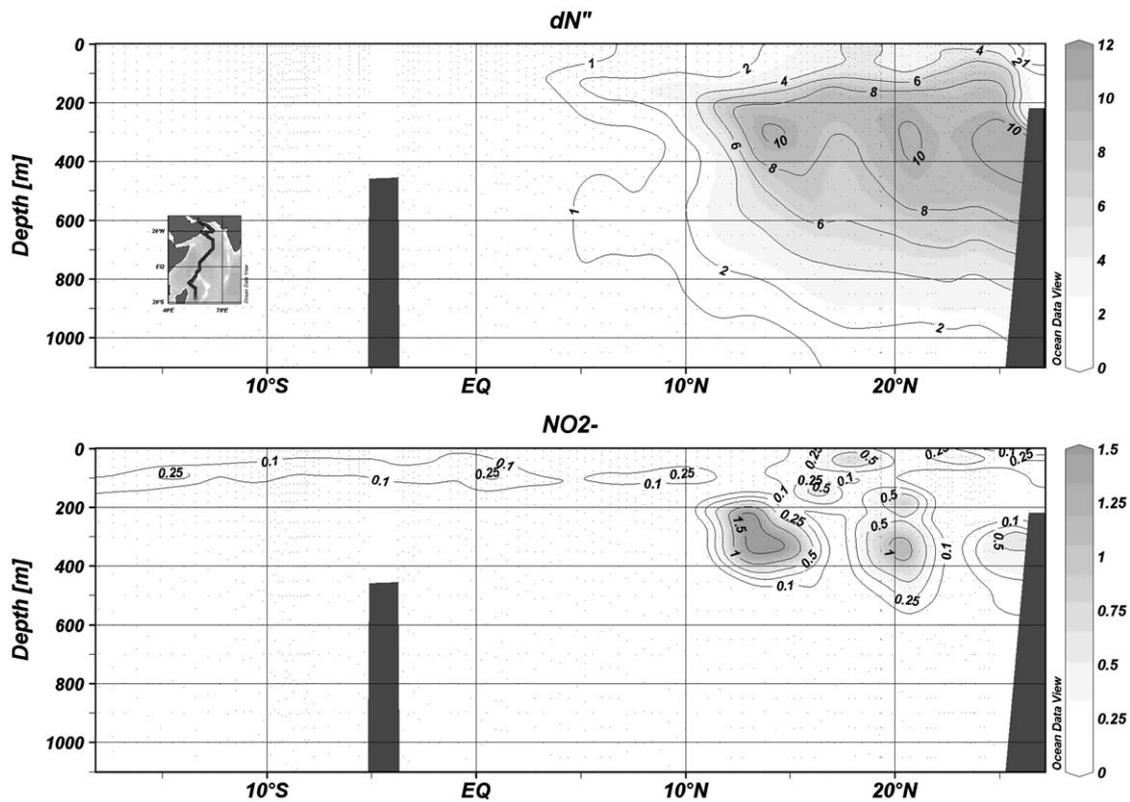


Fig. 9. dN'' (nitrate deficit by denitrification; $\mu\text{mol/kg}$) and nitrite ($\mu\text{mol/kg}$) contours in a latitude-depth space for the cruise i07n data.

the spatial extent of dN'' is much smaller than that of dN . The three dN'' maxima ($\geq 10 \mu\text{mol/kg}$) are accompanied by three secondary nitrite maxima and lie within the oxygen contour line of $2 \mu\text{mol/kg}$ (Fig. 8), which is the upper limit of suboxic condition as defined earlier. The surface dN'' maximum around 18°N in Fig. 9 is related to the upwelling along the Omani coast of the East Africa during the summer SW monsoon. The almost continuous primary nitrite maximum from 27°N to 18°S at depth around 100 m is probably caused by the release of nitrite by bacteria and phytoplankton that reside just below the chlorophyll maximum and reduce nitrate to nitrite internally (assimilative reduction; Karl and Michaels, 2001). This process will be discussed later.

In the plot of dN or dN'' versus potential temperature for the cruise i07n data (north of 4°N only; Fig. 10a), the numbers without double prime indicate possible end members of dN (large change in slope). Peaks 2 and 3 represent, respectively, the dN maximum in the lower and the upper oxyclines. Variation of dN can be explained by the mixing of dN end members in the simple order of 1–5

(Figs. 10a–b). Fig. 10b also shows the inverse relationship between O_2 and dN (or positive correlation between AOU and dN) for samples between end members 1 and 2, and shows a slope $dN \setminus \text{O}_2$ of about $(6 \pm 1) \setminus 130$. Therefore, one may rewrite the remineralization ratios for the deep equatorial Indian Ocean (Li and Peng, 2002) into $P \setminus N \setminus dN \setminus C_{\text{org}} \setminus \text{O}_2 = 1 \setminus (10 \pm 1) \setminus (6 \pm 1) \setminus (94 \pm 5) \setminus (130 \pm 7)$. The $(N + dN) \setminus P$ ratio of 16 is as expected from the model. The numbers with double prime indicate the possible end members of dN'' . Peak 2'' represents the dN'' maximum; 1'' and 3'' the lower and upper boundaries of the denitrification zone; 4'' the subsurface dN'' maximum; and 5'' the upwelled surface dN'' maximum (Fig. 9). Mixing of peak 2'' with 1'' and 3'' forms the broad dN'' maximum within the denitrification zone (Figs. 10a and c). Samples with finite dN'' and O_2 values all can be produced by mixing end members 0'' and 4'' with 1'', 2'' and 3'' (Fig. 10c). The sharp nitrite peak at O_2 less than $2 \mu\text{mol/kg}$ (Fig. 10d) corresponds nicely to the sharp dN'' peak in Fig. 10c.

Our dN and dN'' and the parameter N^* by Deutsch et al. (2001) are conceptually quite different. However, they can be related in magnitude by

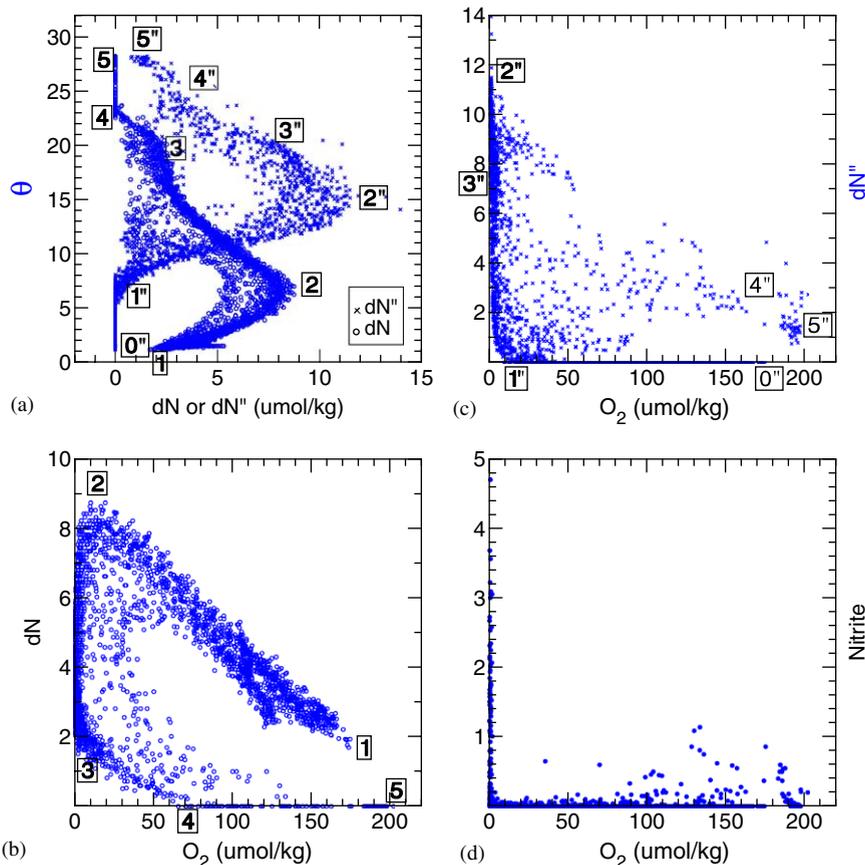


Fig. 10. (a) dN or dN'' vs. θ , (b) O_2 vs. dN , (c) O_2 vs. dN'' , and (d) O_2 vs. NO_2^- for the cruise i07n data north of $4^\circ N$. Numbers without and with double prime represent, respectively, the possible end members of dN and dN'' . See the text for details.

the following relationship, if \bar{N} in Eq. (2b) (Deutsch et al., 2001) is made equal to our N_a

$$-N^* = dN + dN'' \quad (6)$$

Therefore, the $-N^*$ values will give a rough estimate of the total nitrate deficit by partial nitrification and denitrification. For a steady ocean, nitrate converted into N_2 through partial nitrification and denitrification should be balanced by the gain through N_2 fixation as suggested by Gruber and Sarmiento (1997), Deutsch et al. (2001) and Karl et al. (2002). Nitrogen-fixing bacteria are ubiquitous in subtropical and tropical open-ocean habitats (Karl et al., 2002; Church et al., 2005), and may be able to fix enough N_2 to balance the nitrate loss. The recent estimate of the total N_2 fixation by *Trichodesmium* cyanobacterium in the ocean (Capone et al., 2005) indeed suggests this balance. Negative N_a values in shallow water samples with $P < P_o$ in our model roughly correspond to some of the positive N^* values given by Gruber and Sarmiento (1997). A negative

N_a (or positive N^*) only indicates zero N concentration and may suggest the potential site for microbial N_2 fixation, but does not translate into the degree or intensity of N_2 fixation as postulated by Gruber and Sarmiento (1997).

Similar studies of dN and dN'' in the eastern Indian Ocean (including the Bay of Bengal) are summarized in Figs. 11 and 12, using the WOCE data for cruises i08s and i09n (Fig. 1; hereafter as i8s9n). N_a and N_b obtained by curve fitting for the cruise i8s9n are

$$N_a = 16.5(P - 0.20) \quad (7a)$$

and

$$N_b = -2.7573 + 14.6025P + 2.046P^2 - 0.7488P^3 \quad (7b)$$

The dN maximum ($\geq 5 \mu\text{mol/kg}$) again lies within the lower oxycline below the oxygen minimum zone and intersects continental slope sediments at

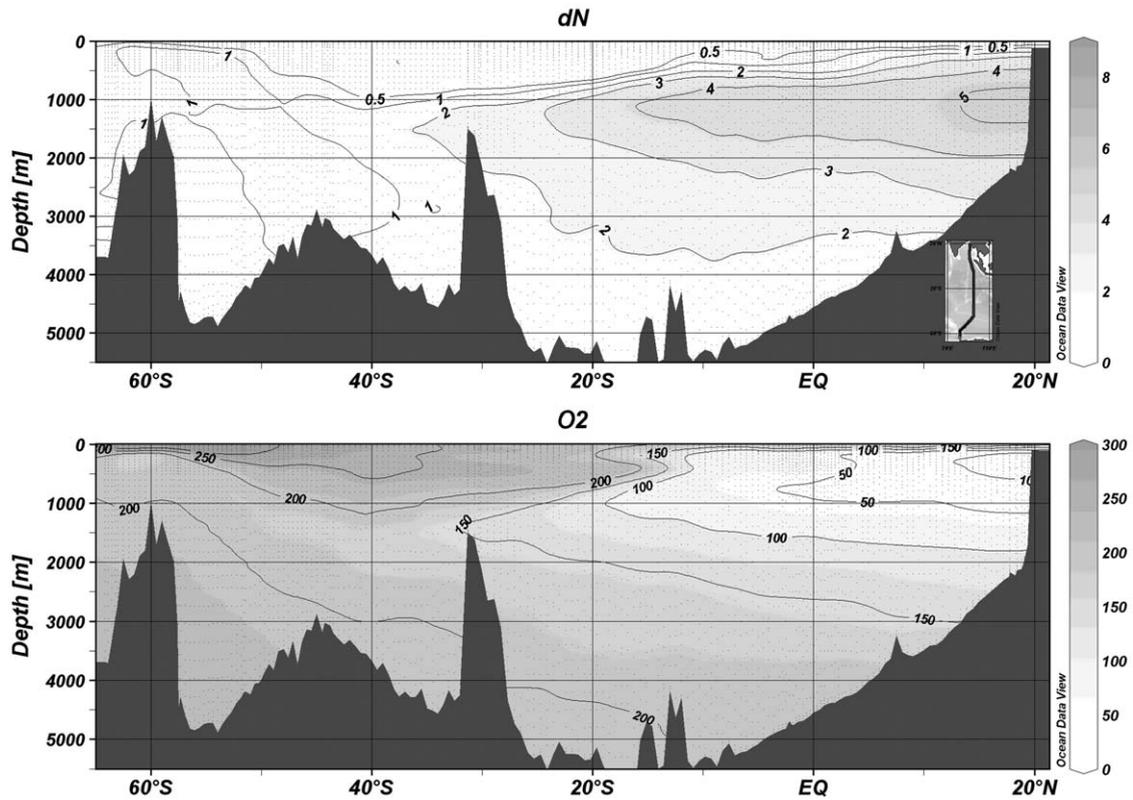


Fig. 11. dN (nitrate deficit by partial nitrification; $\mu\text{mol}/\text{kg}$) and O_2 contours in a latitude-depth space for the cruise i8s9n data.

depth between 800 and 1400 m (Fig. 11). Otherwise, distribution patterns of dN and $-\text{O}_2$ are very similar.

The distribution of dN'' maximum ($\geq 2 \mu\text{mol}/\text{kg}$; Fig. 12a) is confined within a small depth range (50–150 m) and a narrow latitudinal interval (18–21°N). However, it does not associate with the oxygen minimum (Fig. 11b). Therefore, this dN'' maximum must be from sediment inputs. As noticed by Rao et al. (1994), the nitrite maximum in the Bay of Bengal is the primary nitrite maximum and is not related to any denitrification process. The subsurface and surface nitrite maxima (Fig. 12b) are again related to nitrite production/release by bacteria and phytoplankton below or within the chlorophyll maxima. Some surface samples south of 40°S have high P concentration (1.4–2.0 $\mu\text{mol}/\text{kg}$) and high N/P slope (> 16.5), indicating additional oxidation of nitrite into nitrate.

5. Summary and conclusions

1. The newly calculated remineralization ratios along E–W sections of the WOCE data in the deep

Indian Ocean confirm the earlier conclusion that the remineralization ratios change systematically with latitude and from one ocean to another. In addition, the remineralization ratios are also shown to change with water depth. Therefore, any assumption of constancy of remineralization ratios throughout the whole ocean is not warranted.

2. The low remineralization ratio of N/P (considerably less than 16) for deep oxic waters can be best explained by the partial conversion of organic nitrogen into N_2 , N_2O , and NO during oxidation of organic matter in oxyclines by yet unidentified bacteria (i.e. the partial nitrification hypothesis). The unidentified bacteria may resemble *Nitrosomonas europaea* in chemostat cell cultures (Schmidt et al., 2004) and/or the aerobic and anaerobic ammonia oxidizing bacteria coupled within suspended organic particles in a low oxygen CANON reactor (Nielsen et al., 2005). Identification of those unidentified bacteria and the actual microbial reaction pathways (both oxidation and reduction processes) for the partial nitrification process is urgently needed.

3. The average remineralization ratios for the Indian warm water masses ($\theta > \sim 10\text{--}12^\circ\text{C}$) are

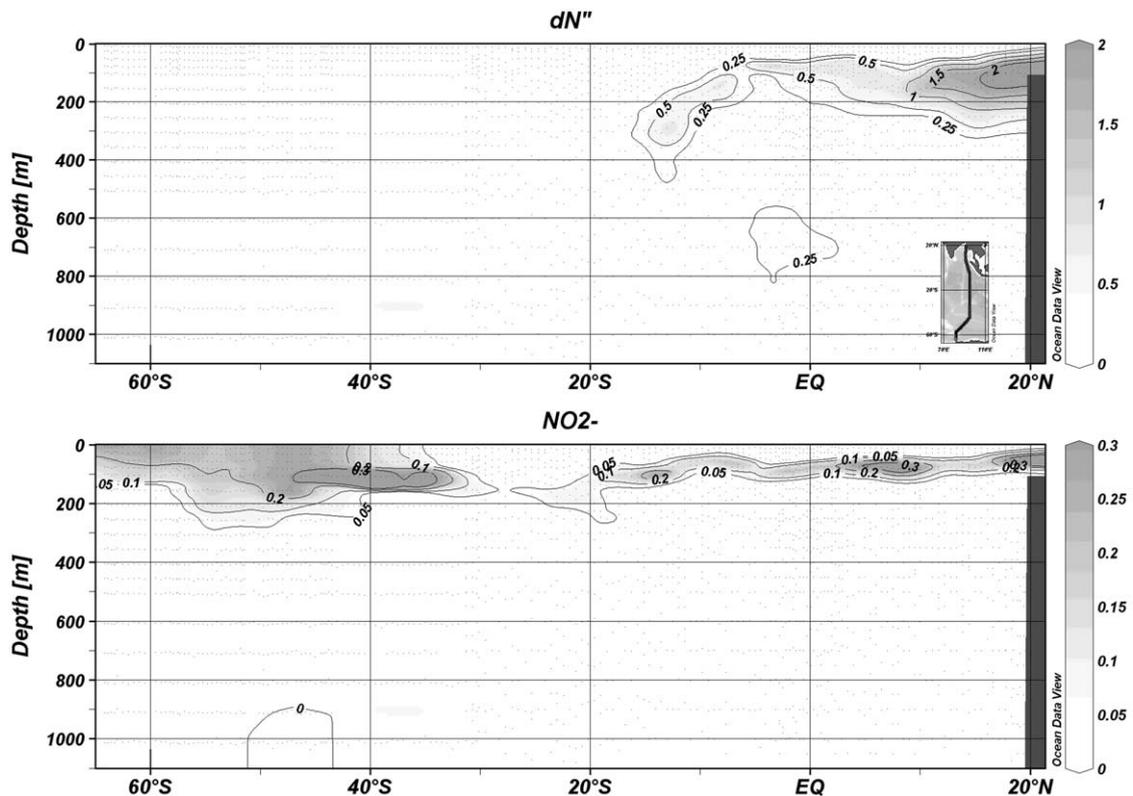


Fig. 12. dN'' (nitrate deficit by denitrification; $\mu\text{mol}/\text{kg}$) and nitrite ($\mu\text{mol}/\text{kg}$) contours in a latitude-depth space for the cruise i8s9n data.

$P \setminus N \setminus C_{\text{org}} \setminus -O_2 = 1 \setminus (15.6 \pm 0.7) \setminus (110 \pm 9) \setminus (159 \pm 8)$. These are comparable to the traditional Redfield ratios ($P \setminus N \setminus C_{\text{org}} \setminus -O_2 = 1 \setminus 16 \setminus 106 \setminus 138$), and are in good agreement with the average suggested by Anderson (1995; $P \setminus N \setminus C_{\text{org}} \setminus -O_2 = 1 \setminus 16 \setminus 106 \setminus 150$) within the given uncertainties.

4. It is time to discontinue the usage of Redfield's formula for marine plankton (CH_2O)₁₀₆(NH_3)₁₆(H_3PO_4), but not his concept. The preferred formula here is $\text{C}_{106}\text{H}_{48}(\text{H}_2\text{O})_{38}(\text{NH}_3)_{16}(\text{H}_3\text{PO}_4)$ by Anderson (1995).

5. Separation of nitrate deficits resulting from aerobic partial nitrification (dN) and anaerobic denitrification (dN'') using empirical equations is shown to be useful and consistent with other observations. The dN maximum coincides with the P and N maximums, lies within the oxycline below the oxygen minimum zone, and intersects the continental slope sediments. In contrast, the dN'' maximum lies within the oxygen minimum zone with $\text{O}_2 < \sim 2 \mu\text{mol}/\text{kg}$ (i.e. denitrification zone), is always associated with a secondary nitrite maximum in the water column, and is in contact with the continental shelf or upper slope sediments.

6. Remineralization ratios for the deep equatorial Indian Ocean can be written as $P \setminus N \setminus dN \setminus C_{\text{org}} \setminus -O_2 = 1 \setminus (10 \pm 1) \setminus (6 \pm 1) \setminus (94 \pm 5) \setminus (130 \pm 7)$. The $(N + dN)/P$ ratio of 16 is consistent with the partial nitrification hypothesis.

7. The spatial extent and magnitude of dN'' are much larger in the Arabian Sea than in the Bay of Bengal. The spatial extent of dN in the Indian Ocean is much wider than that of dN'' , indicating the prevalence of the partial nitrification over the denitrification processes.

8. Conceptually, our dN and dN'' are quite different from the parameter N^* defined by Deutsch et al. (2001). However, they can be roughly related in magnitude by $-N^* = dN + dN''$.

9. Negative N_a values in shallow water samples with $P < P_o$ roughly correspond to some of the positive N^* values given by Gruber and Sarmiento (1997). Negative N_a (or positive N^*) means only zero concentrations of nitrate and nitrite, and may point to potential sites for microbial N_2 fixation, but does not translate into the degree or intensity of N_2 fixation as postulated by Gruber and Sarmiento (1997).

10. The almost continuous primary nitrite maximum from the northern coastal margin down to 40°S at depths around 100 m is probably caused by the release of nitrite by bacteria and phytoplankton that reside just below the chlorophyll.

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