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Seasonal and interannual variations of the nitrogen cycle in the Arabian Sea

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Abstract

The Arabian Sea is strongly influenced by the Asian monsoon and plays an important role as a climate archive and in the marine nitrogen cycle, because bio-available NO_3^- is reduced to dinitrogen gas (N_2) in its mid-water oxygen minimum layer (OMZ). In order to investigate seasonal and interannual variations of the nitrogen cycle, nutrient data were obtained from the literature prior to 1993, evaluated, and compared with data measured during five expeditions in 1995 as well as a research cruise in 2007. Our results imply that the area characterized by a pronounced secondary nitrite maximum (SNM) was by 63 % larger in 1995 than before. This area, referred to as the core of the denitrifying zone, shows strong seasonal and interannual variations driven by the monsoon. During the SW monsoon the SNM retreats eastwards due to the inflow of oxygen-enriched Indian Ocean Central Water (ICW) and it expands westwards during the NE monsoon because of the reversal of the current regime, which allows the propagation of denitrification signals from the Indian shelf into the open Arabian Sea.

On an interannual time-scale an enhanced SW monsoon increases NO_3^- losses by increasing the upwelling-driven carbon export into the subsurface waters. An associate enhanced inflow of ICW increases the transport of denitrification signals from the SNM into the upwelling region and compensates NO_3^- losses by enhanced NO_3^- supply from the Indian Ocean. The latter sustains an enhanced productivity, which in turn transfers denitrification signals into the sedimentary records. On glacial interglacial time scales sea level changes affecting the inflow of ICW seem to increase variations in the accumulation of denitrification tracers in the SNM by reducing the residence time during glacial periods.

1 Introduction

The marine nitrogen cycle, which strongly influences the fertility of the ocean and the sequestration of CO_2 from the atmosphere, is mainly controlled by nitrogen fixation ($N_2 \rightarrow 2NH_3$) and the reduction of NO_3^- to dinitrogen gas ($NO_3^- \rightarrow N_2$) (Brandes and Devol, 2002; Deutsch et al., 2007; Dugdale and Goering, 1967; McElroy, 1983). The reduction of NO_3^- to N_2 referred to as denitrification (Reactions R1–R3), is a combination of different microbial processes such as the NO_3^- (Reaction R1) and NO_2^- reduction (Reaction R2) which can be expressed as follows:

1. Nitrate reduction:

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 260HNO_3 \rightarrow 106CO_2 + 276HNO_2 + H_3PO_4 + 122H_2O \quad \text{(R1)}$$

2. Nitrite reduction:

$$1.75(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 276HNO_2 \rightarrow 185.17CO_2 + 150.23N_2 + 1.75N_2O + 1.75H_3PO_4 + 365.1H_2O \quad \text{(R2)}$$

1. + 2. Denitrification:

$$2.75(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 260HNO_3 \rightarrow 291.17CO_2 + 150.23N_2 + 1.75N_2O + 2.75H_3PO_4 + 487.1H_2O \quad \text{(R3)}$$

Approximately 30 % of the global water-column denitrification occurs in the OMZ of the central and eastern Arabian Sea (Bange et al., 2000; Bulow et al., 2010; Codispoti et al., 2001; Devol et al., 2006; Naqvi, 1987; Nicholls et al., 2007; Ward et al., 2009). In the western Arabian Sea on the highly productive Oman shelf, the co-occurrence of

BGD
10, 19541–19570, 2013

denitrification, dissimilatory NO_2^- reduction (DNRA), and anammox are assumed to be the pathways through which NO_3^- is reduced to N_2 (Jensen et al., 2011). According to Jensen et al. (2011) these reactions can be described as follows:

Denitrification/DNRA:

$$(CH_2O)_{106}(NH_3)_{16}H_2PO_4 + 94.4HNO_3 + 94.4H^+ \rightarrow 106CO_2 + 16NH_4^+ + 16NO_2^- + 39.2N_2 + 145.2H_2O + H_3PO_4 \quad (R4)$$

Anammox:

$$16NH_4^+ + 16NO_2^- \rightarrow 16N_2 + 32H_2O \quad (R5)$$

NO_3^- losses from the OMZ are mainly balanced by inputs of NO_3^- through the northward propagating Indian Ocean Central Water (ICW) sustaining the high productivity in the Arabian Sea (Bange et al., 2000; Brock et al., 1991). In order to study changes of the nitrogen cycle in the Arabian Sea during the last approximately 12 yr we evaluated and compared nutrient data obtained from the literature (Naqvi and Shailaja, 1993; Naqvi, 1991), five expeditions carried out within the framework of US JGOFS in 1995 (Codispoti, 2000; Morrison et al., 1998), and a research cruise with *R/V Meteor* in 2007 (M74 1b; Fig. 1).

2 Study area

The Arabian Sea is strongly influenced by the Asian monsoon, which is driven by summer-heating and winter-cooling of the Asian land mass (Ramage, 1987). Winter-cooling is also a main factor influencing the productivity and the export of organic carbon from the surface into the deep Arabian Sea, because it deepens the mixed layer and thereby entrains nutrients into the euphotic zone (Rixen et al., 2005, 2009; Wiggert et al., 2000, 2002). In summer (SW monsoon) the strong heating forms an atmospheric low over Asia that attracts the SE trade winds blowing as SW winds over the Arabian

Sea after crossing the equator (Fig. 1). The SW winds (SW monsoons) replace the NE winds (NE monsoon) prevailing during winter, reverse the surface ocean circulation including the Somali Current carrying ICW into the western Arabian Sea (Fischer et al., 1996), and cause upwelling off Somalia and Oman (Brock et al., 1991, 1992). Upwelling is the main factor through which the monsoon controls biological productivity and the associated export of organic matter from the sunlit surface ocean into the deep sea during the SW monsoon (Rixen et al., 2000, 2009). During the remineralization of organic matter, oxygen is consumed in the mid-waters, but the lowest mid-water oxygen concentrations occur in the north-eastern Arabian Sea, contrary to the expectations, spatially separated from the highly productive zones in the western and northern Arabian Sea. This spatial separation is caused by the oceanographic conditions characterised by a strong propagation of oxygen-enriched ICW from the south into the high productive western Arabian Sea during the SW monsoon (Fischer et al., 1996; Stramma et al., 1996). The main pathway of this inflow, which occurs mainly in the upper 400 m of the water column, is the Socotra Strait between Somalia and the island of Socotra. The water-masses, which get oxygen-depleted during their passage through the highly productive western Arabian Sea, accumulate in the central and eastern Arabian Sea where the OMZ is most pronounced. Overall the ICW contributes approximately 25 % to the thermocline waters in the upper OMZ (water-depth < 500) which is dominated by the high salinity Arabian Sea Water (ASW, Rixen and Ittekkot, 2005). Towards greater water-depth the contribution of the high salinity ASW decreases and the lower Indian Ocean Deep Water (lower IODW) becomes the dominant water mass.

3 Methods

During the *R/V Meteor* cruise M74/1b to the Arabian Sea, water samples for the determination of nutrients (NO_3^-, NO_2^-, PO_4^{3-}) were obtained from an "Oceanic" rosette water sampler provided with 18 sample bottles. Out of the total 14 stations, 5 (949, 950, 953, 955, and 957) were sampled with a high vertical resolution (25 m) down to a water-

BGD
10, 19541–19570, 2013

depth of 1200 m (Figs. 1 and 2). The rosette water sampler was attached to a Seabird CTD, which was additionally equipped with a fluorescence and an oxygen sensor. Oxygen concentrations measured by using the Winkler method were used to calibrate the oxygen data from the Seabird probe. Nutrients were analyzed on board by using a SKALAR auto-analyzer according to the methods described by Grasshoff (1999). Grasshoff as well as the US JGOFS program (Morrison et al., 1999) followed the standard procedure for the determination of NO_2^- as introduced by Bendschneider and Robinson (1952). After reducing NO_3^- to NO_2^- by using a copperized cadmium column, NO_2^- was analysed by the same method.

$\delta^{15}N$ of NO_3^- ($\delta^{15}N_{NO_3}$) was determined using the "denitrifier method" developed by Sigman et al. (2001). Results are reported in ‰ using the delta notation:

$$\delta^{15}N_{sample} = ((^{15}N/^{14}N)_{sample}/(^{15}N/^{14}N)_{reference} - 1) \cdot 1000 \tag{1}$$

with air N_2 being the reference for $^{15}N/^{14}N$. *Pseudomonas chlororaphis* (ATCC#13985, formerly known as *Pseudomonas aureofaciens*) were used to transform NO_3^- and NO_2^- to N_2O that is subsequently analyzed for its nitrogen isotope values using a Delta Plus XP mass spectrometer. Isotope values were calibrated using IAEA-N3 with an assigned $\delta^{15}N$ value of +4.7 ‰ and USGS-34 ($\delta^{15}N_{NO_3} = -1.8$ ‰; Böhlke et al., 2003). An internal potassium NO_3^- standard was used for further quality assurance. Nitrogen isotope values were corrected using a single point correction referring to IAEA-N3. Since NO_2^- was not removed from the OMZ samples prior to isotope analysis and since *Pseudomonas aureofaciens* used for the "denitrifier method" convert NO_3^- and NO_2^- to N_2O, $\delta^{15}N_{NO_3}$ values from 125 to 400 m water-depth have to be considered as combined N isotope values for NO_3^- and NO_2^-. N isotope values of pure NO_3^- from these water-depths are higher than their N isotope values from mixed NO_3^- plus NO_2^-, because NO_2^- N isotope values from OMZs are negative (Casciotti and McIlvin, 2007; Gaye et al., 2013). The standard deviation for IAEA-N3 was 0.3 ‰, which is in the same range for $\delta^{15}N_{NO_3}$ for at least duplicate measurements of the samples.

BGD
10, 19541–19570, 2013

4 Results and Discussion

4.1 The secondary nitrite maximum (SNM)

In the central and eastern Arabian Sea at oxygen concentrations < 5 µM increased NO_2^- concentrations occur within the upper part of the OMZ (Fig. 2). This NO_2^- accumulation which was first reported in 1933/34 (Gilson, 1937), is referred to as the SNM. NO_2^- is an intermediate product formed during nitrification as well as during NO_3^- reduction (see Reactions R1–R4). Due to the lack of oxygen required for nitrification, the formation of the SNM was assumed to be caused by denitrification (Naqvi, 1991). This view was furthermore supported by profiles showing that the SNM is associated with a pronounced NO_3^--deficit expressed as N^* (Gruber and Sarmiento, 1997), and a pronounced positive excursion of the $\delta^{15}N$ values of NO_3^- (Naqvi et al., 1998; Naqvi, 1991) which could also be seen during our cruise in 2007 (Fig. 2). The enrichment of the heavier isotope ^{15}N in the NO_3^- is caused by the isotopic fractionation during the NO_3^- reduction in the course of which the lighter isotope ^{14}N is preferentially transformed into NO_2^- (Cline and Kaplan, 1975; Mariotti et al., 1981). Bulow et al. (2010) found a linear correlation between denitrification rates and NO_2^- concentrations in the SNM suggesting that NO_2^- concentrations increase within rising denitrification rates. Vice versa NO_2^- concentrations close to zero indicate the absence of denitrification implying that denitrification is mainly restricted to the SNM.

Experimentally determined NO_3^- reduction and NO_2^- re-oxidation rates suggest, in line with hardly detectable denitrification and anammox rates, a mean residence time of 49 yr of water within the OMZ (Jensen et al., 2011; Lam et al., 2011). Such a long residence time in addition to high anammox rates (up to 39 nmol $N_2\,L^{-1}\,d^{-1}$) measured along the Oman shelf lead to the assumption that the NO_3^--deficit produced on the basin's boundary are mainly responsible for the severe NO_3^--deficits seen in the SNM of the whole Arabian Sea (Lam et al., 2011). Low anammox rates in the central Arabian Sea were confirmed also by other experiments (Bulow et al., 2010; Nicholls et al.,

BGD
10, 19541–19570, 2013

2007; Ward et al., 2009). In contrast to Jensen et al. (2011) and Lam et al. (2011) other studies obtained substantially higher denitrification rates (Bulow et al., 2010; Devol et al., 2006; Ward et al., 2009). Considering a mean NO_3^--deficit of 7.8 mol N m^{-2} in the upper 1000 m of the OMZ (Rixen and Ittekkot, 2005) and an area of active denitrification of 1.37×10^{12} m^2 (Naqvi, 1991), the higher denitrification rates of 9.1 nmol L^{-1} d^{-1} result in a mean residence time of water in the OMZ of approximately 10 yr, if one assumes that active denitrification occurs only within the SNM (Fig. 2). Earlier estimates of the residence times vary between 1 and 50 yr (Naqvi and Shailaja, 1993; Sen Gupta and Naqvi, 1984), but the only one study using Trichlorofluoromethane for calculating the residence time suggests, in line with our calculation, a mean residence time of water within the OMZ of 10 yr (Olson et al., 1993). The NO_3^--deficit which can be explained by the mean residence time of Olson et al. (1993) and the denitrification rates measured by Bulow et al. (2010), Ward et al. (2009) and Devol et al. (2006), support currently the original concept of Naqvi (1991) who used the occurrence of the SNM to map the spatial extension of the denitrifying zone. Following Naqvi's concept we use a threshold of > 2 µmol kg^{-1} in order to identify and map the spatial extension of the core of the SNM.

4.2 Spatial expansion of the SNM

For mapping the spatial expansion of the SNM, data from approximately 674 stations north of 10° N were available in 1991 (Naqvi, 1991). These data were obtained almost 50 yr ago during the International Indian Ocean Expeditions (IIOE). Stations where a SNM > 2 µmol kg^{-1} was found were considered to be part of the core denitrifying zone. The resulting map (see Fig. 1) indicates accordingly the maximum expansion of the core of the denitrifying zone prior to1991. However, an uneven data coverage in space and time was assumed to bias the extent of the denitrifying zone (Naqvi, 1991). The main problems were that the data-density was higher during the NE than during the SW monsoon and more data were collected in the north-western than in remaining parts of the Arabian Sea.

BGD
10, 19541–19570, 2013

To reduce problems associated with the spatial coverage all data collected during the five US JGOFS cruises in 1995 were collected along a pre-defined station grid (Figs. 1 and 3). The five US JGOFS cruises revealed a pronounced seasonality of the denitrifying zone with the lowest spatial expansion during the early phase of the SW monsoon (Figs. 3 and 4, Codispoti, 2000; Morrison et al., 1998). During the NE monsoon the denitrifying zone expands westwards. However, in 1995 a SNM was observed at stations (e.g. N4, S6 and S13) at which no SNM was observed prior to 1991 (Fig. 1). In view of data limitation and the fact that these stations in the north and west were characterized by a SNM with NO_2^- concentrations $> 0.5\,\mu mol\,kg^{-1}$ even prior to 1991, we would refrain from postulating a north-westward expansion of the denitrifying zone after 1991. Nevertheless, it seems that in the northern and western Arabian Sea, the area which was characterised by NO_2^- concentrations between 0.5 and $2\,\mu mol\,kg^{-1}$ prior to 1991, revealed NO_2^- concentration $> 2\,\mu mol\,kg^{-1}$ in 1995 (see red broken line in Fig. 1). This represents an expansion of the area known to be characterized by an NO_2^- concentration $> 2\,\mu mol\,kg^{-1}$ from 0.56 to $0.91 \times 10^{12}\,m^2$ and implies an expansion of the known core of the denitrifying zone of 63 %.

4.3 Seasonal variability in the SNM

In order to study processes controlling the seasonal variability all nutrient data, oxygen concentrations, and densities of waters masses within the SNM were averaged (Table 1). The obtained data show a negative correlation between mean oxygen concentrations and the mean NO_3^--deficit expressed as N∗ (Gruber and Sarmiento, 1997). This indicates that decreasing oxygen concentrations favour denitrification in the SNM (Fig. 5a). Dissolved oxygen is not consumed during denitrification or annamox (see Reactions R1–R5). Thus, the correlation between oxygen concentration and NO_3^--deficit implies that lower ventilation favours denitrification and/or that nitrification accompanies denitrification in the SNM. During the JGOFS cruises an oxygen decrease of approximately $0.45\,\mu mol\,O_2\,kg^{-1}$ is associated with an increase of the of $2.2\,\mu mol\,N\,kg^{-1}$ (Fig. 5a). Assuming C/O_2 and C/NO_3 remineralisation ratios of 0.77 and 1.12 during

BGD
10, 19541–19570, 2013

nitrification (Redfield et al., 1963) and, respectively, denitrification (see Reaction R3) we calculated that nitrification contributes on average less than approximately 10 % to the decomposition of organic matter within the SNM.

In the course of the year 1995 the lowest mean oxygen concentration occurred within the SNM during the peak of the SW monsoon (August/September) and during the NE monsoon (January/February, Fig. 5b). Since the organic carbon export flux revealed its peak also during the SW monsoon it is assumed that the enhanced supply of organic matter favours nitrification and the resulting reduced oxygen concentrations additionally denitrification (Table 1, Fig. 5a).

After the SW monsoon when the organic carbon flux is relatively low the oxygen concentrations in the SNM revealed its second pronounced drop between November and December (Fig. 5b). This decrease could be associated with a reversing current regime, in the course of which the westwards flowing water masses lead to the westward expansion of the SNM during this time of the year (Fig. 4, cruise ttn53). The Indian shelf is known for low oxygen waters, partly even due to eutrophication (Naqvi et al., 2000). The measured denitrification rates along the Indian shelf were with 32 µmol L^{-1} d^{-1}, 3.5 times higher as within the SNM and almost as high as the anammox rates on the Oman shelf (Devol et al., 2006; Jensen et al., 2011; Naqvi et al., 2000). Accordingly it is assumed that the export of NO_3^--deficit produced on the Indian shelf along with westward moving water masses contributes to NO_3^--deficit seen in the SNM during the NE monsoon.

4.4 Interaction between the SNM in the central and eastern Arabian Sea and the upwelling region in the western Arabian Sea

Considering that mixing in the ocean's interior occurs along isopycnical surfaces we additionally averaged all seawater properties in the western Arabian Sea within the density range (26.3–25.5 kg m^{-3}) in which the SNM is located in the central and eastern Arabian Sea (Table 1). The mean oxygen concentrations within this water mass show the highest oxygen concentrations during the peak of the NE monsoon (Fig. 5b). At

BGD
10, 19541–19570, 2013

this time winter cooling and in the western Arabian Sea additionally enhanced wind speeds (Rixen et al., 1996) increase vertical mixing so that the depth of the mixed layer exceeds that of the euphotic zone. Light limitation and a reduced export of organic carbon as seen in January/February are the consequences (Fig. 5d, Rixen et al., 2005). Reduced carbon fluxes and increased ventilation due to deep mixing could accordingly explain the high mid-water oxygen concentrations as well as the interrupted westward expansion of the SNM during the NE monsoon as seen in 1995 (Fig. 4).

After the spring reversal of the current regime the oxygen concentrations in the SNM continued to rise (Fig. 5b), the SNM withdrew eastwards (Fig. 4)and in the western Arabian Sea the oxygen concentration reached a maximum almost simultaneously with the organic carbon flux towards the end of the SW monsoon in September (Fig. 5d). This implies in line with model studies (Anderson et al., 2007) that a reinforced propagation of oxygen-enriched ICW through the Strait of Socotra into the region off Oman prevents the westwards expansion of SNM by increasing the oxygen concentration in the western Arabian Sea and until the peak of the SW monsoon also in SNM.

During the peak of the NE and the SW monsoon the difference between the oxygen concentrations in western Arabian Sea and the SNM were extremely high. During the intermonsoons in the absence of strong atmospheric forcing iscopycninal mixing seems to reduce the gradient between these two regions. Since the lower the gradient, the higher the NO_3^--deficits in the western Arabian Sea (Fig. 5c), it is assumed that denitrification signals in the upwelling region are caused by the propagation of these signals from SNM into the upwelling region.

4.5 Interannual variability

In order to investigate changes between the SW monsoon 1995 and that in 2007, JOGFS sites were revisited during a research cruise with *R/V Meteor* (M74 1b, Figs. 1 and 3). During this cruise upwelling was still present over the Oman shelf as indicated by enhanced phosphate (> 1 µmol kg^{-1}) and chlorophyll concentrations in the surface waters (Fig. 6). As indicated by chlorophyll concentrations > 0.25 mg m^{-3} the upwelling-

BGD
10, 19541–19570, 2013

driven blooms could even be seen at station 950/S9 in the core of denitrifying zone (Figs. 1 and 6).

To compare the 1995 and the 2007 expeditions only those JGOFS stations will be considered in the following discussion, which were revisited in 2007 (Fig. 3c and d). This comparison shows that the spatial expansion of the denitrifying zone during the SW monsoon in 2007 was much larger than during the SW monsoon in 1995 (Fig. 7). Similar to the NE monsoon, it showed a pronounced westward expansion and a weak SNM could even be seen at station 950/S6, which was absent during the late SW monsoon 1995 (Fig. 8b). The mean NO_2^- concentrations in the SNM were higher in 2007 than observed at any time in 1995 (Table 1). This implies in line with the linear correlation between denitrification rates and NO_2^- concentrations (Bulow et al., 2010) that denitrification rates were on average higher in 2007 than in 1995. Nevertheless the NO_3^--deficit was lower and the oxygen concentration higher than expected from the trend seen in 1995 (Fig. 5a). Contrary to NO_2^-, which is constantly formed and consumed, NO_3^--deficits and oxygen concentration are accumulative water mass tracers, which are strongly influenced by the residence time of water in the SNM. Enhanced denitrification rates associated with a lower ratio between NO_3^--deficits and oxygen concentrations could, for example, result from stronger SW monsoons. This could enhance denitrification rates and thus NO_2^- concentrations by increasing the upwelling-driven organic carbon export into the SNM. On the other hand an associated strengthening of the propagation of ICW into the Arabian Sea could lower the NO_3^--deficit to oxygen ratio by reducing the residence time of water within the SNM. But was the SW monsoon in 2007 stronger than the one in 1995?

Sea surface temperatures (SST) are often-used as an indicator of upwelling strength (Rixen et al., 1996). However, its use became even more problematic since the impact of global warming penetrates through mixing and deep water formation also into the ocean's interior and warms the subsurface water that wells up along the coasts (Levitus et al., 2000). In order to reduce this problem induced by global warming, we decided to calculate the cooling caused by upwelling as the SST difference between

BGD
10, 19541–19570, 2013

the spring-intermonsoon and the following SW monsoon (Fig. 9). Since the beginning of satellite-derived SST measurements in 1982, the mean SW monsoon cooling in the upwelling influenced western Arabian Sea between 13 and 23° N and 55 and 65° E was 1.82 °C. The decade between 1997 and 2007 was in general characterized by SW monsoons all revealing a cooling above average (Fig. 9). Between 1997 and 2004 the decreasing SSTs and increasing chlorophyll concentrations off Somalia were linked to the shrinking EURASIAN snow cover and it was suggested that global warming started to increase the monsoon-driven upwelling (Goes et al., 2005). In the western Arabian Sea off Oman chlorophyll concentrations reveal not such a clear trend but were also enhanced during the SW monsoons between 1998 and 2005 compared to those determined during the SW monsoons from 2006 to 2009 (Naqvi et al., 2010). However, according to the cooling indicator the SW monsoon 2007 seemed to be part of a series of monsoons, which were stronger than the one in 1995 (Fig. 9). Enhanced upwelling driven organic carbon fluxes could explain the – compared to year 1995 – low oxygen concentrations in the western Arabian Sea in 2007 (Table 1, Fig. 5d). Relatively low oxygen concentrations and high organic fluxes are also in the line with the extremely high anamox rates measured by Jensen et al. (2011) during the same cruise M74 1b off Oman. However, an associated enhanced inflow of ICW reducing the residence time of water within the OMZ could be another process decreasing the oxygen concentrations in the upwelling region by accelerating the isopycnial exchange with the SNM. Consequences are rising oxygen concentrations in the SNM as discussed before and a low difference in the oxygen concentration between these two regions increasing NO_3^- deficits in the western Arabian Sea as seen already on the seasonal time-scale (Fig. 5c).

In the western Arabian Sea densities between 26.3 and 25.5 $kg\,m^{-3}$ occur at water-depths around 250 m. Since this is the water-depth from which the upwelled water originates (Rixen et al., 2000) it is suggested that denitrification signals entering the western Arabian Sea via isopycnical mixing are brought to surface by upwelling.

BGD
10, 19541–19570, 2013

This supports paleooceanographic studies showing a strong correlation between the monsoon intensity, upwelling strength, and the accumulation of denitrification tracers such as $\delta^{15}N$ of NO_3^- that is preserved as organic nitrogen in sediments of the Arabian Sea (Altabet et al., 1999, 2002; Suthhof et al., 2001). The paleorecords also show baseline shifts within the system: Although lower $\delta^{15}N$ values are assumed to indicate a weaker monsoon-driven productivity during glacial times, $\delta^{15}N$ values during warmer phases of the glacial periods (interstadials) are as high as during the early Holocene as the monsoon was assumed to be extremely strong (Altabet et al., 1999, 2002; Herzschuh, 2006; Suthhof et al., 2001). This strong variability during the glacial times in the course of which the $\delta^{15}N$ values exceed even those measured during Holocene could be a consequence of a longer residence times due to weaker monsoon and the glacial sea level low stand. Since the latter narrows the passage through the Socotra Strait both factors could have reduced inflow of ICW and therewith extend the residence time of water in the OMZ of the Arabian Sea and reduced the upwelling.

5 Conclusions

Our results indicate that the area characterized by an NO_2^- concentration $> 2\,\mu mol\,kg^{-1}$ within the SNM referred to the core of the denitrifying zone was by 63 % larger in the year of 1995 than assumed earlier. Nevertheless, based on the available data, it is difficult to distinguish between trends and the pronounced seasonal and interannual variability seen in the spatial expansion of the core of the denitrifying zone. The latter follows mainly the monsoon-driven seasonal reversal of the current regime. During the SW monsoon the SNM retreats eastward due to the inflow of oxygen-enriched ICW and enhanced organic carbon export seems to increase denitrification rates within the SNM. During the NE monsoon the SNM expands westwards because of the reversal of the current regime, which allows the propagation of denitrification signals from the Indian shelf into the open Arabian Sea. On interannual time-scale stronger SW monsoons seem to increase NO_3^- losses by enhancing the upwelling driven carbon export.

BGD
10, 19541–19570, 2013

An associated reinforced propagation of ICW increases the transport of accumulative denitrification tracers from the SNM into the upwelling region and could compensate to some extend the enhanced NO_3^- losses by increasing the NO_3^- inputs from the Indian Ocean into the Arabian Sea. The latter sustains a high upwelling-driven productivity and the associated carbon export transfers denitrification signals into sediments where they are preserved on geological time-scales. On glacial interglacial time-scales larger changes of the inflow of ICW due to e.g. sea level changes and the resulting variation of water mass transport across morphological sills could lead to larger variations in the accumulation of denitrification tracers in the SNM during glacial times.

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BGD

10, 19541–19570, 2013

Seasonal and interannual variations of the nitrogen cycle

T. Rixen et al.

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Table 1. Cruises, dates, phases of the monsoon, nutrient and oxygen concentrations as well as temperatures and salinities averaged for the core of the denitrifying zone (SNM) indicated by NO_2^- concentrations $> 2\,\mu mol\,kg^{-1}$ and oxygen concentrations $< 5\,\mu mol\,kg^{-1}$ and at the same density range within the western Arabian Sea west of 62.5° E. Only (West) samples for which both NO_3^- and PO_4^{3-} were measured were considered.

Cruise	Date	Phases of the monsoon	NO_2^-	N^*	PO_4^{3-}	NO_3^-	O_2	Temp.	Salinity
			$\mu mol\,kg^{-1}$					°C	
SNM									
Ttn49	18 Jul–13 Aug 1995	SW – early	3.11	14.56	2.48	19.98	0.92	15.77	35.86
Ttn50	14 Aug–13 Sep 1995	SW – late	3.19	15.29	2.53	19.98	0.72	17.06	35.89
M74	**18 Sep–4 Oct 2007**	**SW – late**	**3.80**	**14.45**	**2.40**	**18.94**	**1.43**	**15.68**	**35.76**
Ttn53	29 Oct–25 Nov 1995	Inter	3.48	13.78	2.27	17.54	1.12	18.49	35.84
Ttn54	30 Nov–26 Dec 1995	NE – early	3.36	15.91	2.57	19.98	0.69	16.25	35.85
Ttn43	8 Jan–11 Feb 1995	NE – peak	3.12	15.89	2.57	19.88	0.65	15.66	35.82
Ttn45	14 Mar–8 Apr 1995	NE – late	3.25	15.08	2.53	20.23	0.76	16.44	35.81
WEST									
Ttn49	18 Jul–13 Aug 1995	SW – early	0.00	8.57	2.40	25.68	3.49	15.34	35.81
Ttn50	14 Aug–13 Sep 1995	SW – late	0.01	7.74	2.40	25.56	8.57	15.12	35.74
M74	**18 Sep–4 Oct 2007**	**SW – late**	**0.04**	**10.06**	**2.36**	**23.25**	**2.07**	**15.95**	**36.00**
Ttn53	29 Oct–25 Nov 1995	Inter	0.03	10.23	2.47	24.90	1.41	15.55	35.84
Ttn54	30 Nov–26 Dec 1995	NE – early	0.01	10.00	2.44	24.64	3.26	15.97	35.94
Ttn43	8 Jan–11 Feb 1995	NE – peak	0.01	7.36	2.39	26.88	9.84	15.26	35.76
Ttn45	14 Mar–8 Apr 1995	NE – late	0.07	9.51	2.43	25.13	4.71	15.79	35.87

BGD
10, 19541–19570, 2013

Seasonal and interannual variations of the nitrogen cycle

T. Rixen et al.

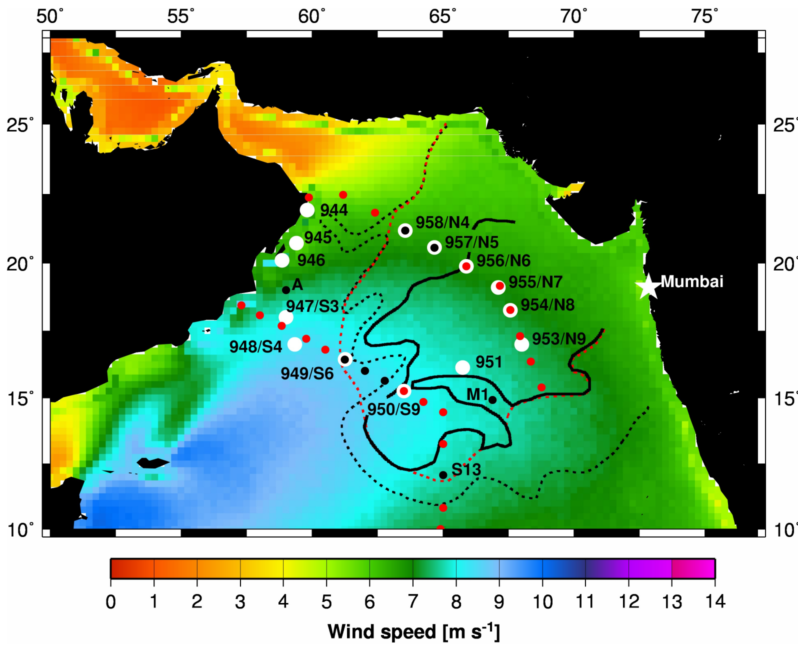

Fig. 1. Mean SW monsoon winds speeds over the Arabian Sea (Rixen et al., 1996). The area of enhanced wind speeds indicates the Findlater Jet. The black lines were redrawn from Naqvi and Shailaja (1993) and show the expansion of the area in which NO_2^- concentrations within the SNM are > 0.5 µmol kg^{-1} (broken line) and > 2 µmol kg^{-1} (solid line). Circles represent the stations covered during the US JGOFS expeditions in 1995 (red and black) and the *R/V Meteor* cruise M74 1b in 2007 (white). The M74 stations are indicated by the numbers 944–958 and the US JGOFS station numbers are A, M1, S(1–13), N(1–11). The station at which nitrite concentrations > 2 µmol kg^{-1} were observed outside the area marked by Naqvi and Shailaja (1993) in 1995 are indicated by the black circles. Based on these stations and the former 0.5 µmol kg^{-1} line the expansion of the area in which NO_2^- concentrations within the SNM are > 2 µmol kg^{-1} in 1995 was drawn (red broken line).

BGD

10, 19541–19570, 2013

Seasonal and interannual variations of the nitrogen cycle

T. Rixen et al.

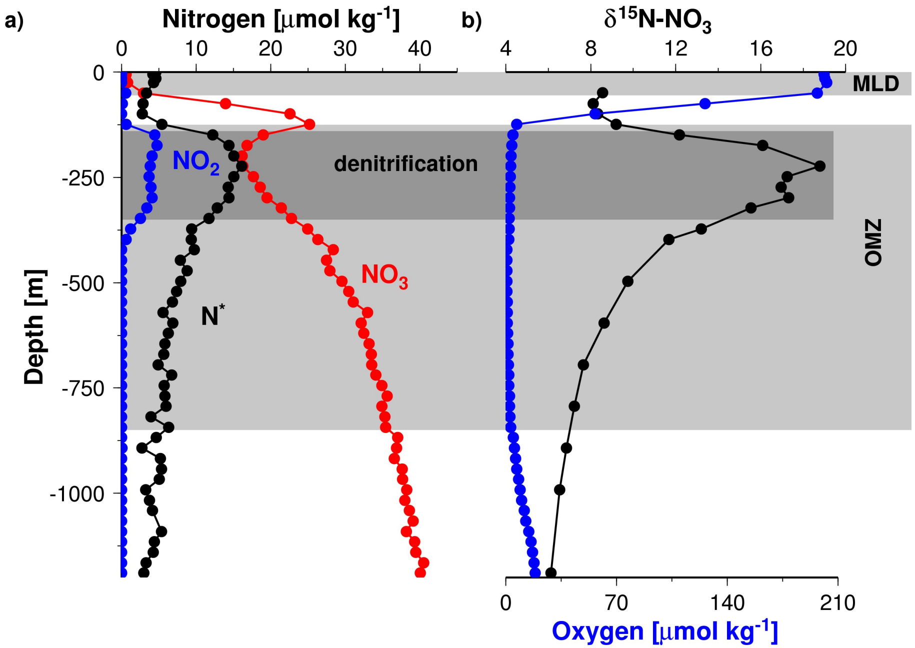

Fig. 2. **(a)** Vertical profiles of nitrite, NO_3^- and N* and **(b)** of oxygen and δ^{15}N of NO_3^- and nitrite ($\delta^{15}N_{NO_3}$) at station 953 (Fig. 1).

BGD
10, 19541–19570, 2013

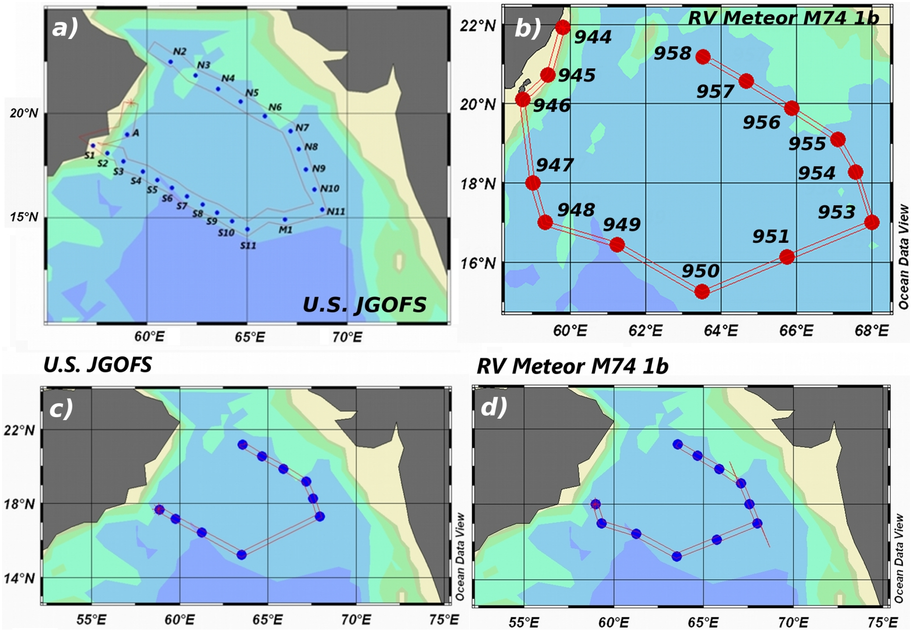

Fig. 3. Cruise tracks and stations of the US JGOFS cruises in 1995 **(a)** and the *R/V Meteor* cruise M74 1b in 2007 **(b)** as well as the transects used to produce the cross sections in Fig. 4 **(a)**, Fig. 5 **(b)**, and Fig. 6 **(c, d)**.

BGD
10, 19541–19570, 2013

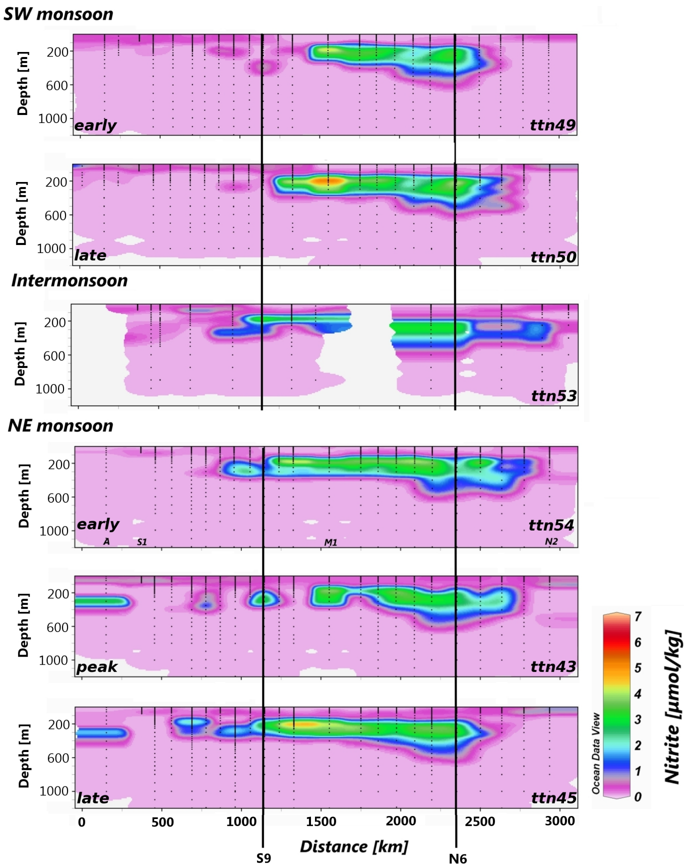

Fig. 4. Cross sections showing the seasonal distribution of nitrite concentrations along the JOGFS transects from the Oman coast (station A, S1) towards the central and eastern Arabian Sea (stations M1) and the northern part of the eastern Arabian Sea (M1 – N_2, compare Fig. 3a, Table 1). The vertical black line shows the maxima expansion of the core of the denitrifying zone in 1993.

BGD
10, 19541–19570, 2013

Seasonal and interannual variations of the nitrogen cycle

T. Rixen et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

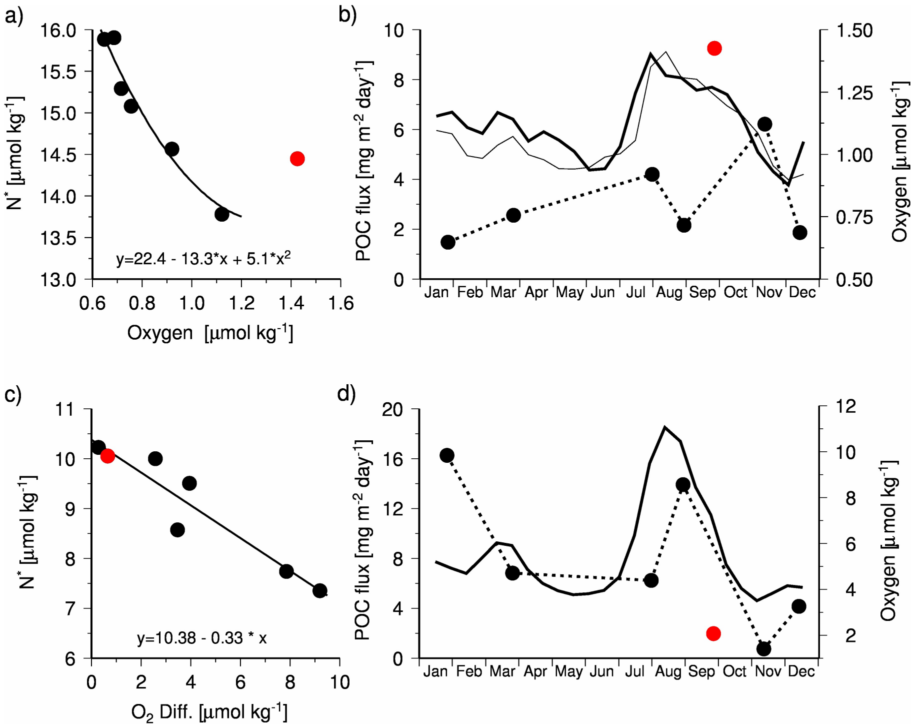

Fig. 5. NO_3^--deficits expresses as N^* vs. oxygen concentrations **(a)** as well as differences between oxygen concentrations in the SNM and the western Arabian Sea vs. N^* **(c)**. Monthly mean organic carbon fluxes measured by sediment traps at a water-depth of 3000 m in the central (bold line) and eastern Arabian Sea (thin line) and western Arabian Sea **(d)** (Haake et al., 1993; Rixen et al., 2005) as well as the mean oxygen concentrations in the SNM **(b)** and the western Arabian Sea **(d)**. Black circle indicate the US JGOFS data and the red circle the one derived from the cruise M74 1b. The oxygen and N^* data are given in Table 1.

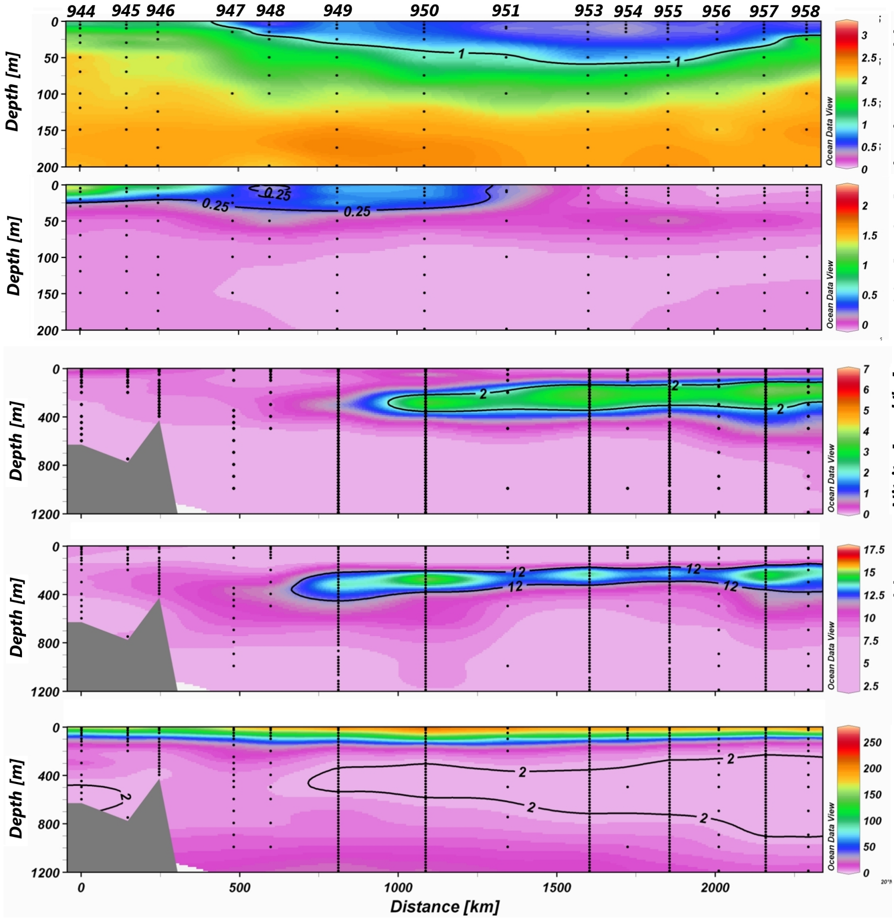

Fig. 6. Transects from the western (944) towards the central (950) and eastern Arabian Sea (951–958) obtained during the *R/V Meteor* cruise M74 1b in 2007 (see Table 1). The transect is given in Fig. 3b.

BGD

10, 19541–19570, 2013

Seasonal and interannual variations of the nitrogen cycle

T. Rixen et al.

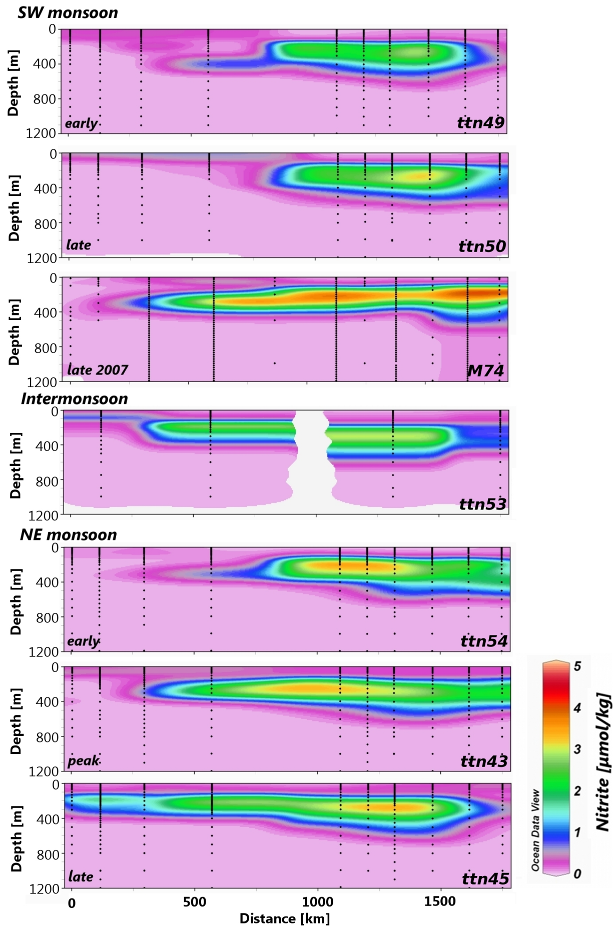

Fig. 7. Cross sections showing the seasonal distribution of nitrite concentration during the US JOGFS cruises in 1995 as well as during the late SW monsoon 2007 (see Fig. 1 and Table 1). The transects are given in Fig. 3c and d.

BGD
10, 19541–19570, 2013

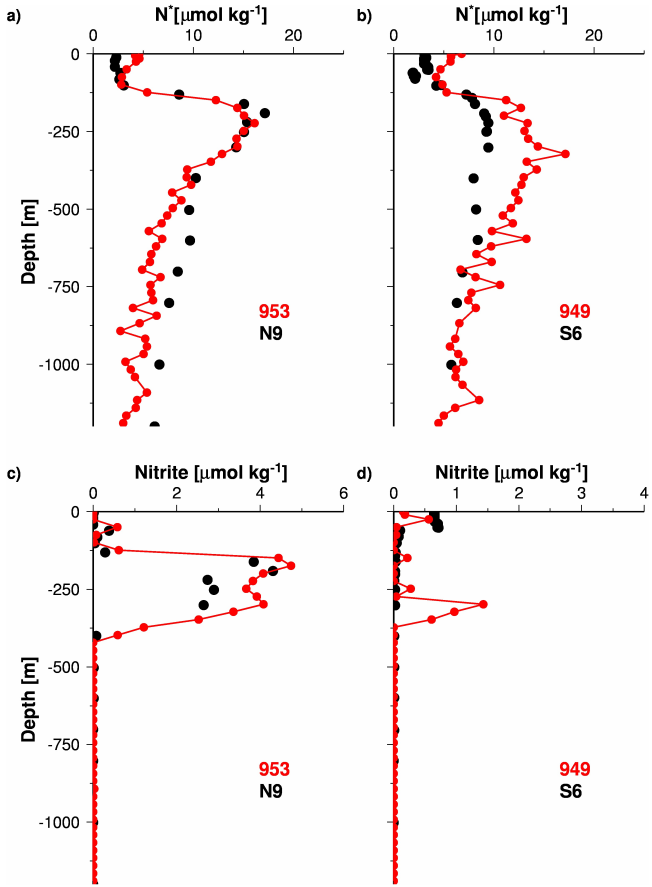

Fig. 8. Profiles of NO_3^--deficits expresses as N* **(a, b)** and NO_2^- **(c, d)** obtained during the JGOFS late SW monsoon 1995 cruise ttn50 in the eastern (N9) and central (S6) Arabian Sea (black circles) as well as during the M74 1b cruise at the same stations (red circles, stations 953 and 949).

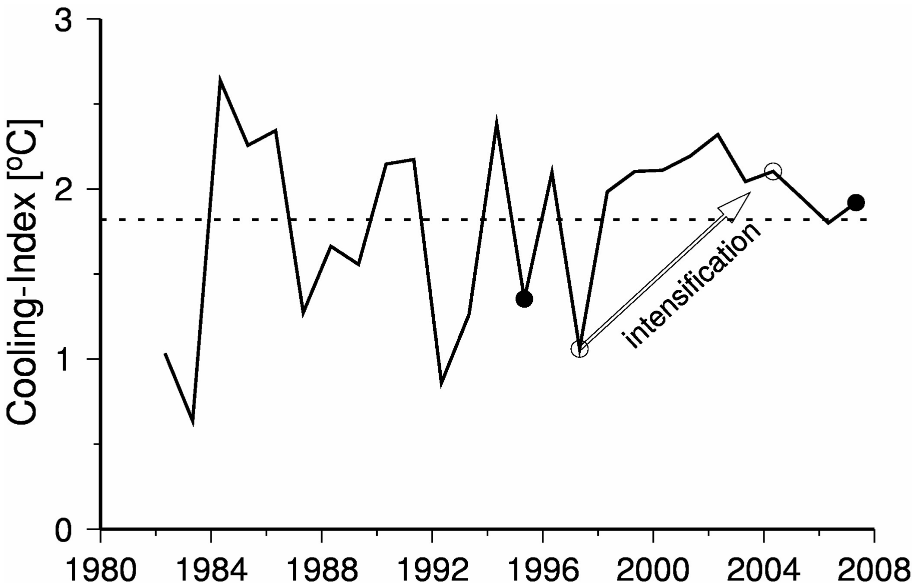

Fig. 9. The cooling-index calculated as SST difference between the spring-intermonsoon and the SW monsoon. Data were obtained from Smith et al. (2008) and averaged for the upwelling influenced western Arabian Sea between 13 and 23° N and 55 and 65° E. The dotted line shows the mean upwelling-driven cooling of 1.82 °C, the black circles indicate the SW monsoon 1995 and 2007, and open circles the SW monsoon 1997 and 2004. The arrow indicates the periods during which Goes et al. (2005) obtained the data which lead to the assumption that global warming enhances the upwelling-driven productivity in the Arabian Sea.

BGD
10, 19541–19570, 2013