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A revised nitrogen budget for the Arabian Sea

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Abstract. Despite its importance for the global oceanic nitrogen (N) cycle, considerable uncertainties exist about the N fluxes of the Arabian Sea. On the basis of our recent measurements during the German Arabian Sea Process Study as part of the Joint Global Ocean Flux Study (JGOFS) in 1995 and 1997, we present estimates of various N sources and sinks such as atmospheric dry and wet depositions of N aerosols, pelagic denitrification, nitrous oxide (N_2O) emissions, and advective N input from the south. Additionally, we estimated the N burial in the deep sea and the sedimentary shelf denitrification. On the basis of our measurements and literature data, the N budget for the Arabian Sea was reassessed. It is dominated by the N loss due to denitrification, which is balanced by the advective input of N from the south. The role of N fixation in the Arabian Sea is still difficult to assess owing to the small database available; however, there are hints that it might be more important than previously thought. Atmospheric N depositions are important on a regional scale during the intermonsoon in the central Arabian Sea; however, they play only a minor role for the overall N cycling. Emissions of N_2O and ammonia, deep-sea N burial, and N inputs by rivers and marginal seas (i.e., Persian Gulf and Red Sea) are of minor importance. We found that the magnitude of the sedimentary denitrification at the shelf might be ~17% of the total denitrification in the Arabian Sea, indicating that the shelf sediments might be of considerably greater importance for the N cycling in the Arabian Sea than previously thought. Sedimentary and pelagic denitrification together demand ~6% of the estimated particulate organic nitrogen export flux from the photic zone. The main northward transport of N into the Arabian Sea occurs in the intermediate layers, indicating that the N cycle of the Arabian Sea might be sensitive to variations of the intermediate water circulation of the Indian Ocean.

1. Introduction

The northwestern part of the Indian Ocean is defined as the Arabian Sea. It is surrounded by the African and Asian continents to the west, north, and east. The Arabian Sea experiences extremes in atmospheric forcing during the southwest (SW) monsoon (from late May to September) and the northeast (NE) monsoon (from December to March), which lead to the greatest seasonal variability of biological productivity observed in any ocean basin. The Arabian Sea contains diverse biogeochemical features such as upwelling, oligotrophic, and low-oxygen environments. The latter lies between 150- and 1000-m depth and represents the thickest oxygen minimum zone (OMZ) found in the world's oceans today. The OMZ of the Arabian Sea is the site of intense denitrification processes ($NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$) [*Mantoura et al.*, 1993; *Naqvi*, 1994]. About 20% of the global denitrification occurs in the Arabian Sea (which covers only ~2% of the global ocean area), which thus plays a major role in the global oceanic nitrogen (N) cycle [*Gruber and Sarmiento*, 1997; *Howell et al.*, 1997]. For further details about the oceanographic and biogeochemical aspects of the Arabian Sea, the reader is referred to literature compilations presenting results from various international research programs such as the ongoing Joint Global Ocean Flux Study (JGOFS)–Arabian Sea Process Study [*Burkill*, 1999; *Burkill et al.*, 1993; *Desai*, 1992; *Ittekkot and Nair*, 1993; *Krishnaswami and Nair*, 1996; *Lal*, 1994; *Smith*, 1998; *Van Weering et al.*, 1997]. A comprehensive overview about the historical, geological, hydrographic, chemical, and biological aspects of the Arabian Sea in the context of the Indian Ocean is given in a recently published book by *Rao and Griffiths* [1998].

Despite its importance for the global oceanic N cycle, little is known about the N fluxes in the Arabian Sea [*Naqvi et al.*, 1992; *Somasundar et al.*, 1990]. On the basis of our 1995–1997 measurements during the German JGOFS–Arabian Sea Process Study and recent literature data, we present a revised N budget for the Arabian Sea in order to reduce the uncertainties existing in previous estimates and discuss possible controlling mechanisms of the N cycle.

2. Methods

The data used in the present assessment were mostly collected during the 1995 R/V *Meteor* cruise legs M32/3 (1995) and M32/5 (July–August) and during the 1997 R/V *Sonne* cruise legs SO117 (March), SO119 (May–June), and SO120 (June–July),

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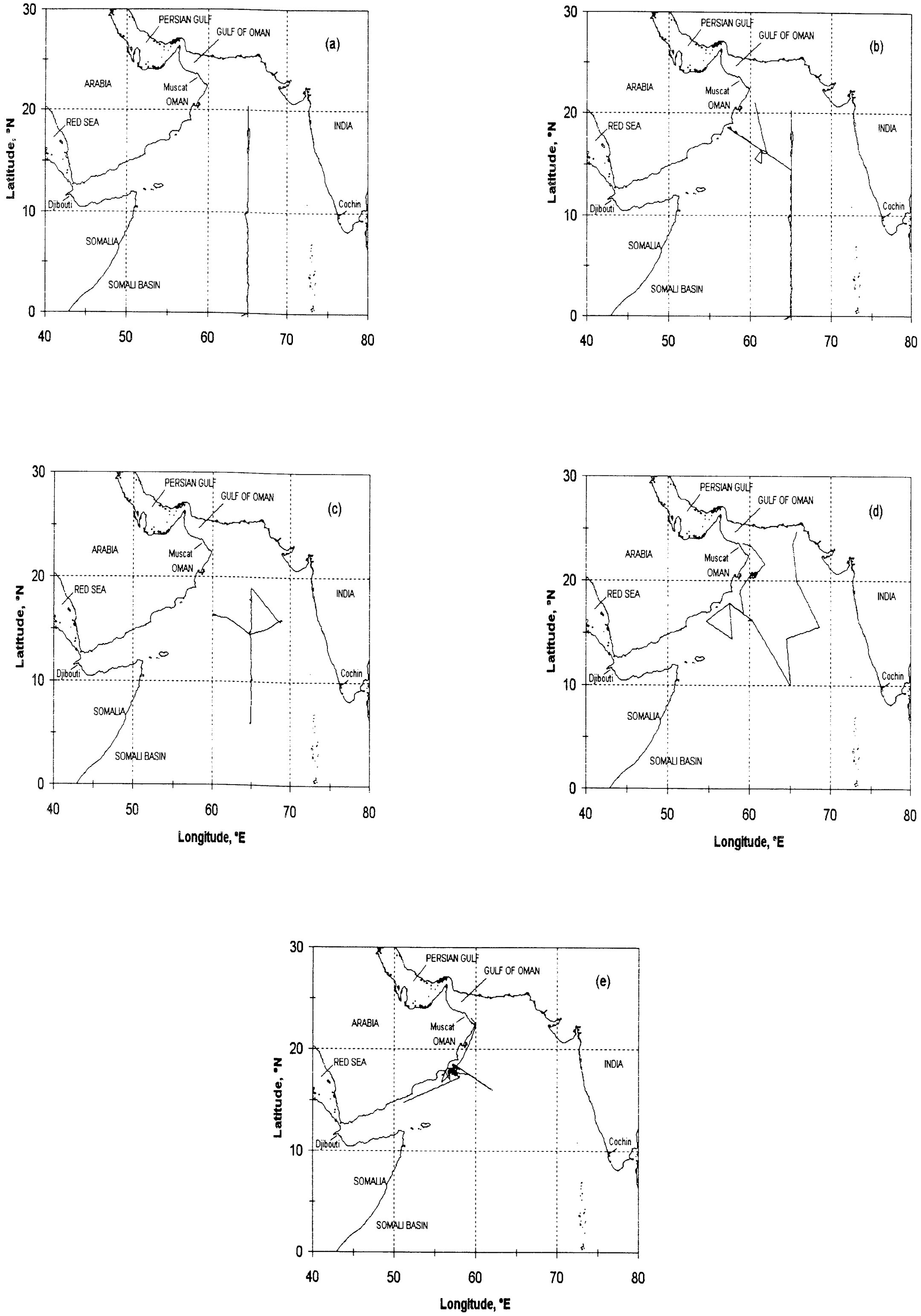

Figure 1. Maps of the Arabian Sea showing the cruise tracks of R/V *Meteor* and R/V *Sonne* during the German JGOFS–Arabian Sea Process Study in (a) May 1995 (M32/3, Muscat, Oman to Victoria, Seychelles), (b) July–August 1995 (M32/5, Victoria to Muscat), (c) March 1997 (SO117, Cochin, India to Muscat), (d) June–July 1997 (SO119, Muscat to Muscat), and (e) June–July 1997 (SO120, Muscat to Djibouti, Djibouti).

mainly in the central and western Arabian Sea (Figure 1). Ambient aerosol samples were collected during legs M32/3, M32/5, and SO117. Two low-volume collectors were used to collect aerosol samples for nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+), which were analyzed by ion chromatography in the laboratory after the cruises. For details of the analytical method applied see *Johansen et al.* [1999]. Dissolved nitrous oxide (N_2O) was determined on board with a gas chromatograph equipped with an electron capture detector. Further details of the N_2O analysis system for surface water measurements are described by *Bange et al.* [1996]. Sea water temperature, dissolved nutrients, dissolved oxygen (O_2), primary production, and meteorological data were taken from German JGOFS data sets compiled for each cruise leg (F. Pollehne et al., unpublished data, 1996; B. Zeitzschel et al., unpublished data, 1996, 1998; W. Balzer et al., unpublished data, 1998; V. Ittekkot et al., unpublished data, 1998). The data collected within the framework of the German JGOFS–Arabian Sea Process Study are available from the German JGOFS Data Management Office (http://www.ifm.uni-kiel.de/pl/dataman/dmpag1.html).

Subsamples from 14 sediment cores (Figure 2) [*Sirocko et al.*, 1991] covering the late Holocene (0–8000 BP) were used to determine the total nitrogen contents. The analytical methods for the determination of the total nitrogen contents are described in detail by *Haake et al.* [1993]. In brief, total nitrogen was measured by a catalytic high-temperature combustion method and subsequent thermal conductivity detection.

In order to obtain reliable and consistent flux estimates, the southern boundary of the Arabian Sea was set to 6°N spanning a line from the Somali coast to the southern tip of Sri Lanka (Figure 2). Measurements in the area south of 6°N are rare, since most studies focus on the central and coastal parts of the Arabian Sea. Consequently, we used ocean areas calculated for the Arabian Sea north of 6°N (excluding the Red Sea and the Persian Gulf). We used 4.93 x 10^{12} m^2 for the total Arabian Sea area, 0.51 x 10^{12} m^2 for the shelf areas (0–200 m), and 4.16 x 10^{12} m^2 for the area of the Arabian Sea with water depths below 1000 m. Area values were calculated from the bathymetric data set of the Climate Data Library provided by the International Research Institute for Climate Predictions and the Lamont–Doherty Earth

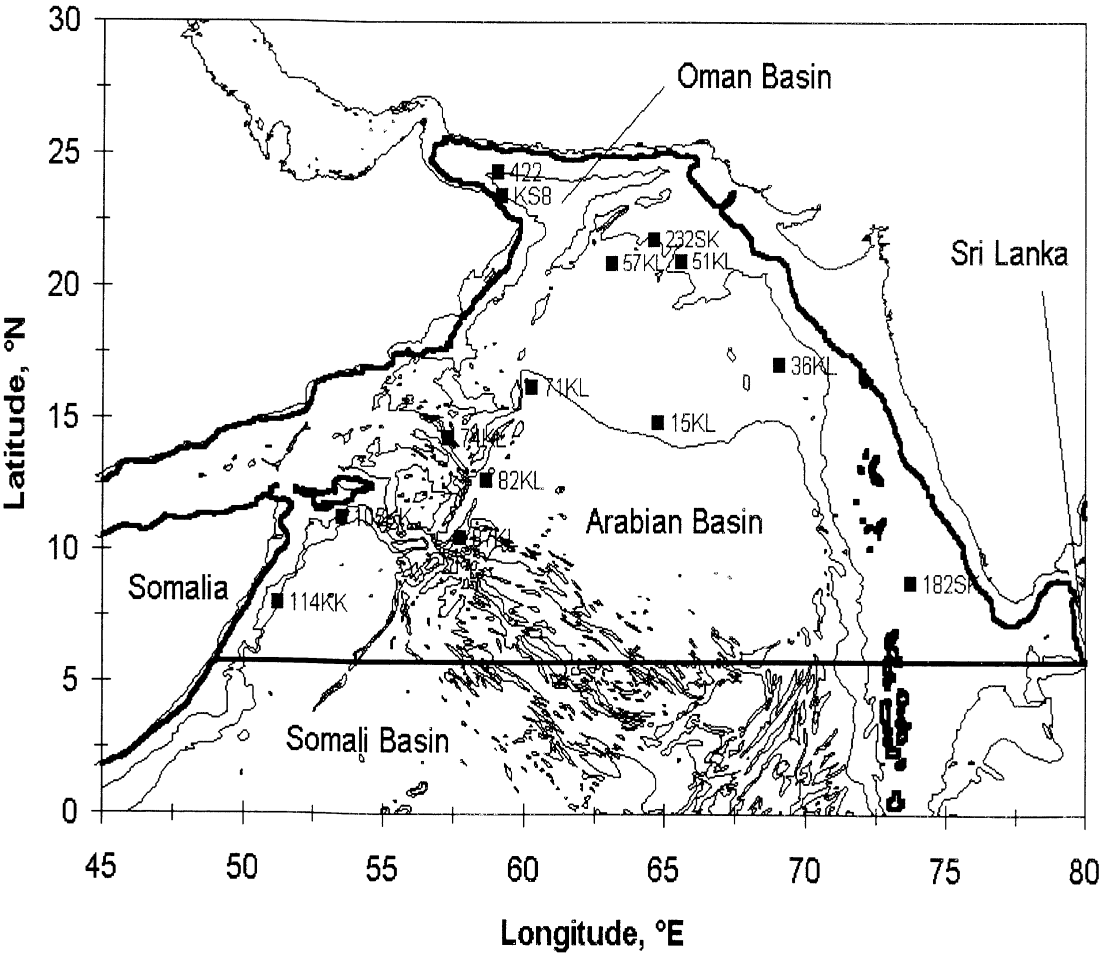

Figure 2. Map of the Arabian Sea showing the locations of the sediment cores. Major basins of the Arabian Sea and depth contours (200 m, thick line; 3000 and 4000 m, thin lines) are indicated. The vertical line represents 6°N which was used as the southern boundary for our flux estimates. (The contours were taken from the 1997 edition of the General Bathymetric Chart of the Oceans published by the British Oceanographic Data Centre, Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside, United Kingdom.)

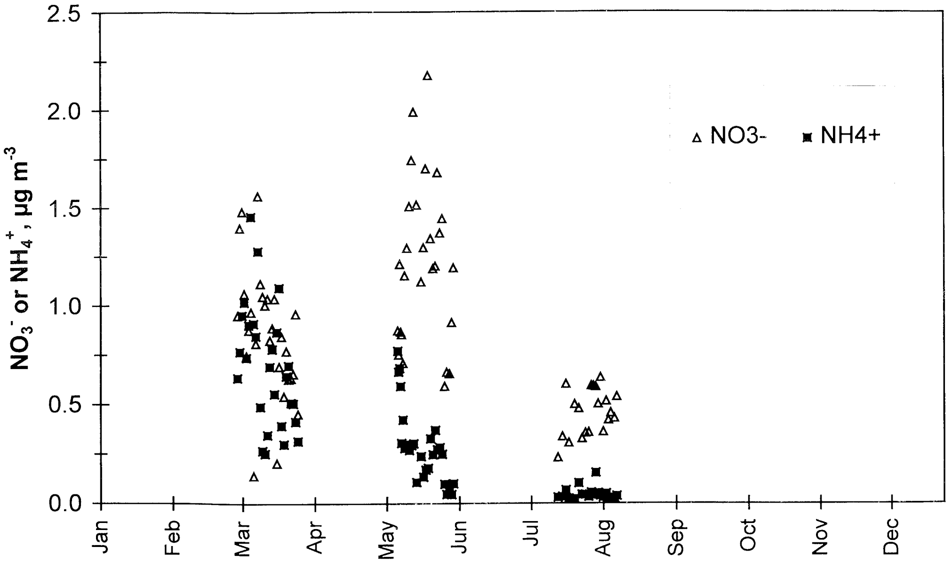

Figure 3. Aerosol concentrations of NO_3^- and NH_4^+ over the Arabian Sea during March 1997 (leg SO120), May 1995 (leg M32/3), and July–August 1995 (leg M32/5). Filled squares stand for NH_4^+ and open triangles stand for NO_3^-.

Observatory of Columbia University (Palisades, New York). Data are available from http://ingrid.ldgo.columbia.edu/SOURCES/WORLDBATH/.

3. Results: Nitrogen Sources

3.1. Atmospheric Dry Deposition of NO_3^-, NO_2^-, and NH_4^+

Figure 3 shows the concentrations of NO_3^- and NH_4^+ during the spring intermonsoon (May 1995), the SW monsoon (July–August 1995), and the decline of the NE monsoon (March 1997). Minimum concentrations of aerosol NO_3^- and NH_4^+ were observed during the SW monsoon. Maximum concentrations of NO_3^- were measured during the spring intermonsoon, whereas NH_4^+ showed maximum concentrations during the declining NE monsoon. We observed a trend towards higher NH_4^+ concentrations when approaching the coastal regions of Pakistan and Oman. NO_2^- concentrations, however, were generally near or below the detection limit of ~0.01 $\mu g\ m^{-3}$. An overview of the mean aerosol concentrations derived from our measurements and comparable literature data is given in Table 1. Our data are consistent with the aerosol data that are available from the Arabian Sea region [*Gibb et al.*, 1999; *Krishnamurti et al.*, 1998; *Rhoads et al.*, 1997; *Sarin et al.*, 1999; *Savoie et al.*, 1987]. As expected, the concentrations of NH_4^+ and NO_3^- over the Arabian Sea are controlled by the seasonal variabilities of the source areas of the sampled air masses [*Tindale and Pease*, 1999; *Pease et al.*, 1998]. Owing to the seasonal northward shift of the Intertropical

Table 1. Mean Aerosol Concentrations of Nitrate, Nitrite, and Ammonium over the Arabian Sea North of 6°N

Date	Region of the Arabian Sea	NO_3^-	NO_2^-	NH_4^+	References
Jan.–May 1979	central	0.43 ± 0.31 (34)	no data	no data	*Savoie et al.* [1987]
Jan.–May 1979	southwest/Somali Coast	1.01 ± 0.59 (39)	no data	no data	*Savoie et al.* [1987]
Jan. 1996	Indian Coast	5.05 ± 2.39 (4)	no data	3.25 ± 1.98 (4)	*Krishnamurti et al.* [1998]
Feb. 1997	central/east	1.9 ± 1.0 (9)	no data	no data	*Sarin et al.*[1999]
Feb.–March 1995	central/east/Indian Coast	2.4 ± 1.0 (8)	no data	no data	*Sarin et al.* [1999]
March 1997	central	0.87 ± 0.33 (27)	< 0.01	0.69 ± 0.31 (27)	this study
April 1995	central/southeast	1.71 ± 0.62 (9)	no data	0.71 ± 0.33 (9)	*Rhoads et al.* [1997]
April–May 1994	central/east	1.1 ± 0.4 (10)	no data	no data	*Sarin et al.* [1999]
May 1995	central	1.32 ± 0.39 (22)	0.03 ± 0.05 (15)	0.34 ± 0.18 (22)	this study
July–Aug. 1995	central/west/Coast of Oman	0.47 ± 0.10 (17)	0.03 ± 0.01 (12)	0.05 ± 0.03 (17)	this study
July–Aug. 1995, 1996	central/east/Indian Coast	0.5 ± 0.2 (15)	no data	no data	*Sarin et al.* [1999]
Aug.–Oct. 1994	central/west	no data	no data	0.04	*Gibb et al.* [1999]
Nov.–Dec. 1994	central/west	no data	no data	0.12[a]	*Gibb et al.* [1999]
Average		1.52	0.02	0.74	

Concentrations are in $\mu g\ m^{-3}$. Values are given as mean ± standard deviation. Numbers of samples are given in parentheses.

[a] On the basis of a mean of 6925 pmol m^{-3} for aerosol phase NH_4^+; the published value (see *Gibb et al.* [1999], Table 4) is not correct (S.W. Gibb, personal communication, 1999).

Convergence Zone, which is most pronounced during the SW monsoon in the summer months, air masses in the central Arabian Sea sampled from late May until August 1995 were mainly from the Southern Hemisphere, whereas those sampled during March 1997 were from the Northern Hemisphere. While air masses from the Southern Hemisphere (i.e., the region of the southern Indian Ocean) are comparably pristine, air masses originating from the Northern Hemisphere are polluted by N emissions due to industrial and agricultural activities of the countries surrounding the Arabian Sea [*Krishnamurti et al.*, 1998; *Rhoads et al.*, 1997].

We computed mean annual concentrations of 1.52 and 0.74 µg m^{-3} for NO_3^- and NH_4^+, respectively (Table 1). The dry deposition flux (F_d) was calculated as

$$F_d = V_d\, C_{ae},$$

where C_{ae} is the aerosol concentration of NO_3^- or NH_4^+ and V_d is the dry deposition velocity. Estimates of V_d are associated with considerable uncertainties because V_d depends on complex interactions of various parameters such as wind speed, particle size, relative humidity, and sea surface roughness [*Duce et al.*, 1991]. Thus, to simplify estimates of particle deposition fluxes, values of V_d only accounting for the aerosol size distribution are frequently used. NO_3^- over the oceans is usually associated with large sea salt particles, whereas NH_4^+ is usually found on small particles [*Duce et al.*, 1991; *Schäfer et al.*, 1993]. This is in good agreement with our results from the SO117 expedition, where on average 74% of the NO_3^- occurred in the coarse fraction (>3 µm) and on average 93% of the NH_4^+ occurred in the fine fraction (<3 µm). Estimates for the dry deposition velocity (V_d) range from 0.03 x 10^{-2} m s^{-1} for submicrometer aerosol particles to 6.0 x 10^{-2} m s^{-1} for large sea salt particles [*Duce et al.*, 1991]. By applying deposition velocities of 1.5 x 10^{-2} m s^{-1} for NO_3^- and 0.05 x 10^{-2} m s^{-1} for NH_4^+ (both values were adopted from *Schäfer et al.* [1993]) and an Arabian Sea area of 4.93 x 10^{12} m^2, we estimated the annual dry deposition fluxes to be 0.80 Tg N for nitrate and 0.04 Tg N for ammonium.

3.2. Atmospheric Wet Deposition

Since direct measurements of N compounds in rain water in the Arabian Sea area are rare and not representative [*Duce et al.*, 1991; *Gibb et al.*, 1999], we roughly estimated the wet deposition with the equation given by *Duce et al.* [1991]:

$$F_r = P\, S\, C_{ae}\, \rho_a{}^{1}\, \rho_w,$$

where F_r is the wet deposition in g m^{-2} yr^{-1}, P represents the rain rate in mm yr^{-1}, S is the dimensionless scavenging ratio, C_{ae} is the aerosol concentration in µg m^{-3}, ρ_a and ρ_w are the densities of air and water, respectively. The values for ρ_a and ρ_w were taken as 1200 g m^{-3} and 1 x 10^6 g m^{-3}, respectively [*Duce et al.*, 1991]. The mean annual rainfall over the Arabian Sea is ~780 mm yr^{-1}, as retrieved from the Indian National Satellite for the years 1987 until 1990 [*Ramesh Kumar and Prasad*, 1997]. Mean scavenging ratios of 330 and 200 for NO_3^- and NH_4^+, respectively, were obtained from *Duce et al.* [1991]. The mean aerosol concentrations were taken from the compilation in Table 1. We calculated a mean wet deposition of 150 mg N m^{-2} yr^{-1} (Table 2). By applying an area of 4.93 x 10^{12} m^2, the wet deposition of inorganic nitrogen to the Arabian Sea was extrapolated to be of the order of 0.74 Tg N yr^{-1}.

Cornell et al. [1995] speculated about a considerable contribution of dissolved organic N to the atmospheric wet deposition of N, even in remote marine areas. Thus our estimate might be an underestimation because measurements of dissolved organic N in rain samples from the Arabian Sea are not available.

4. Results: Nitrogen Sinks

4.1. Pelagic Denitrification

As mentioned in the introduction, the OMZ of Arabian Sea is the site of intense denitrification. In order to quantify the amount of denitrification, we calculated the nitrate deficit (ΔN) which is a measure for the N transformed by the reduction of NO_3^- and NO_2^- to N_2 and N_2O. There are various approaches to estimate ΔN [*Howell et al.*, 1997; *Naqvi*, 1994]. Here we use the "NO" approach which was applied previously for the Arabian Sea by *Naqvi and Sen Gupta* [1985] and *Mantoura et al.* [1993]. The concept of "NO", defined as $[O_2] + r\,[NO_3^-]$ with $r = 9.1$ [*Minster and Boulahdid*, 1987], was introduced as a quasi-conservative water mass tracer by *Broecker* [1974]. In Figure 4, "NO" is plotted against the potential temperature on the basis of the data sets from July–August 1995 (M32/5) and June–July 1997 (SO120). (A thorough data quality check indicated a lower data quality of the NO_3^- data sets from the other legs; thus these data were not considered.) By excluding the data points from the surface to the upper boundary of the OMZ (potential density $\sigma_\theta > 25.7$) and those affected by denitrification ($O_2 < 0.25$ mL L^{-1}), we found a good correlation between potential temperature and "NO", which represents the expected mixing line (["NO"]$_{exp}$) in the case that the OMZ is not affected by denitrification. Using the linear regression for ["NO"]$_{exp}$, we calculated ΔN as follows:

$$\Delta N = ([\text{"NO"}]_{exp} - [O_2])/9.1 - [NO_3^-] - [NO_2^-].$$

Then the ΔN values were integrated over the depth range of the O_2-depleted OMZ ($O_2 < 0.25$ mL L^{-1}); however, stations where the O_2-depleted OMZ is in contact with the sediments were not considered, to avoid any bias because of possible sedimentary denitrification signals. The integrated ΔN values range from 1.0 to 3.6 mol m^{-2}. We found a slight trend of increasing ΔN values toward the coast off Oman during July–August 1995. A similar trend was observed for the apparent nitrate utilization as calculated by *Mintrop et al.* [1999]. The maximum integrated ΔN was found at 18.1°N, 58.0°E in the western part of the Arabian Sea and not in the central part as one might expect because of the

Table 2. Estimate of the Wet Deposition of N Compounds in the Arabian Sea

	Concentration,[a] µg m^{-3}	Scavenging Ratio	Wet Deposition,[b] g N m^{-2} yr^{-1}
NO_3^-	1.52	330	0.0736
NO_2^-	0.02	330	0.0013
NH_4^+	0.74	200	0.0748
Sum			0.150

[a] Mean concentrations taken from Table 1.

[b] Calculated by using an annual mean rain rate for the Arabian Sea of 780 mm [*Ramesh Kumar and Prasad*, 1997].

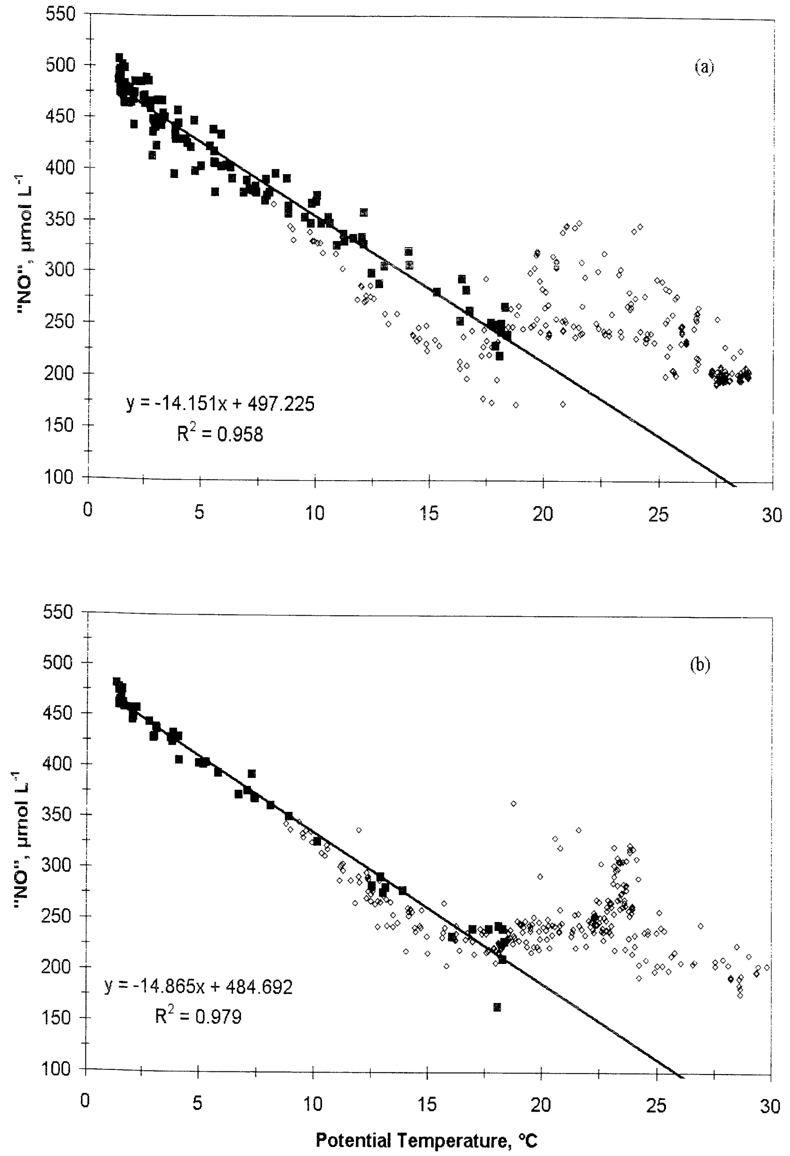

Figure 4. "NO" versus potential temperature: (a) July–August 1995 (M32/5) and (b) June–July 1997 (SO120). Filled squares stand for "NO" with $\sigma_\theta > 25.7$ and $O_2 > 0.25$ mL L^{-1} and were used for the linear regression.

area distribution of the secondary NO_2^- maximum, which is often used as an indicator for the occurrence of denitrification in the OMZ [*Naqvi*, 1991]. The occurrence of the secondary NO_2^- maximum is most pronounced in the central Arabian Sea and not in its western part [*Morrison et al.*, 1998; *Naqvi*, 1991].

The mean integrated ΔN values were 2.5 ± 0.6 (July–August 1995) and 1.6 ± 0.7 mol m^{-2} (June–July 1997), indicating a slight trend; however, a conclusive interpretation is difficult because of a possible bias by the interannual variability of the Arabian Sea. With the overall mean ΔN of 2.2 ± 0.7 mol m^{-2}, which is in excellent agreement with the recently calculated mean integrated ΔN of 2.3 ± 0.5 mol m^{-2} (data from January–March and July–August 1995) by *Howell et al.* [1997], it is possible to estimate the loss of nitrogen within the OMZ, assuming an area for the denitrification of 1.95 x 10^{12} m^2 [*Naqvi*, 1987] and a ventilation time of 1–10 years [*Naqvi and Shailaja*, 1993; *Olson et al.*, 1993]. We computed a total integrated ΔN of 59 Tg N and annual loss fluxes of 6–60 Tg N yr^{-1} (with an average of 33 Tg N yr^{-1}), which are in agreement with recent estimates (12–34 Tg N yr^{-1}) [*Howell et al.*, 1997; *Mantoura et al.*, 1993; *Naqvi and Shailaja*, 1993; *Yakushev and Neretin*, 1997]. The applied area for the denitrification affected OMZ is 30% higher than the revised value of 1.37 x 10^{12} m^2 recently estimated by *Naqvi* [1991]. However, using a larger area appears more appropriate to account for the area distribution of denitrification (see discussion of the trend of ΔN above).

4.2. N_2O Loss to the Atmosphere

Figure 5 shows a plot of our N_2O surface measurements in 1995 [*Bange et al.*, 1996] and 1997 [*Bange et al.*, 1998] versus sea surface temperatures (SSTs). Low SSTs in the range of 18°–28°C, characteristic for the seasonally occurring coastal upwelling and filament structures, show significantly increased

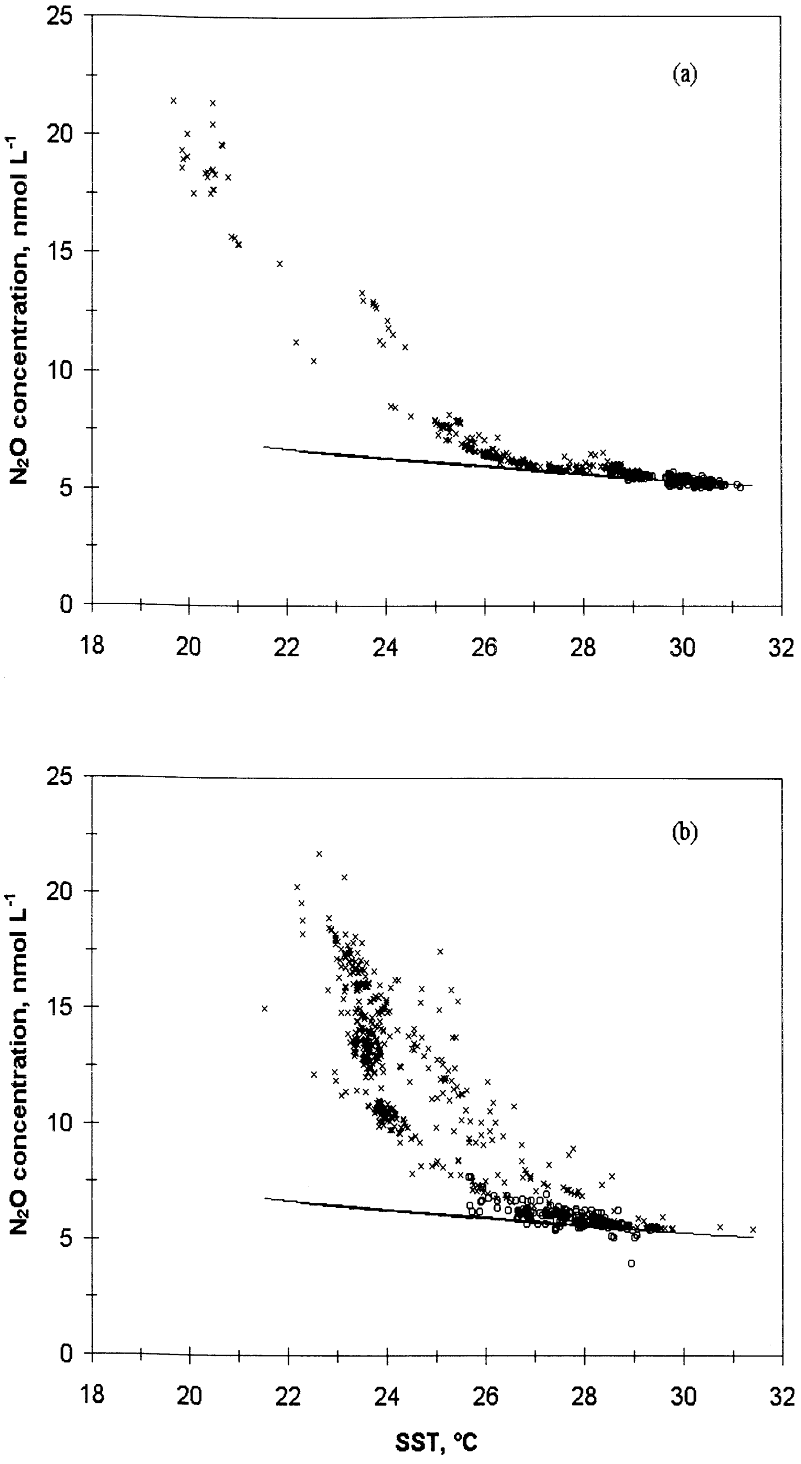

Figure 5. Dissolved N_2O in surface water of the Arabian Sea versus SST: solid lines represent equilibrium N_2O concentrations. (a) 1995 (circles stand for May and crosses stand for July–August) and (b) 1997 (circles stand for March and crosses stand for June–August). Data from May 1997 are not shown.

N_2O concentrations, whereas in the central Arabian Sea (typical range of SST is 26°–31°C), N_2O concentrations near the equilibrium are observable during the whole year. A similar variation of dissolved N_2O with SST was observed for the coastal upwelling area in the southwestern Arabian Sea (i.e., Somali Basin) [*De Wilde and Helder*, 1997].

On the basis of our data from the 1995 and 1997 campaigns, we reassessed the N_2O emissions from the Arabian Sea. The N_2O-exchange flux, F in pmol m^{-2} s^{-1}, can be parameterized as

$$F = k_w (C_w - C_a),$$

where k_w is the gas-transfer coefficient, C_w is the seawater concentration, and C_a is the equilibrium water concentration calculated using the corresponding atmospheric dry mole fraction. To calculate k_w, we used the trilinear k_w/wind speed relationship from *Liss and Merlivat* [1986] (LM86) or, alternatively, the quadratic k_w/wind speed relationship established by *Wanninkhof* [1992] (W92). The coefficients k_w were adjusted by multiplying with $(Sc/600)^{-n}$ ($n = 2/3$ for wind speeds ≤3.6 m s^{-1} and $n = 0.5$ for wind speeds >3.6 m s^{-1}) for LM86 and $(Sc/660)^{-0.5}$ for W92. Sc is the Schmidt number for N_2O, calculated using empirical equations for the kinematic viscosity of seawater [*Siedler and Peters*, 1986] and the diffusivity of N_2O in water [*Broecker and Peng*, 1974]. The measured wind speeds were normalized to 10-m height (u_{10}) by using the relationship of *Garratt* [1977]. We structured our data into those from the central Arabian Sea, the coastal upwelling areas, and filaments (i.e., open-ocean upwelling) area. Then we calculated mean flux densities and emissions for the three oceanographic regimes from the observed flux densities (Table 3).

For the spring intermonsoon there is no interannual trend in the N_2O emissions, whereas for the SW monsoon a shift from the coastal upwelling of the dominant source region in 1995 to the central Arabian Sea as the dominant source region in 1997 is obvious. This trend is driven by the variability of the wind speed (u_{10}) and the N_2O concentration difference ($\Delta C = C_w - C_a$) across the ocean–atmosphere interface (see definition of the flux density above). During 1995 and 1997 the mean ΔC for the central Arabian Sea during the SW monsoon were almost identical: 0.30 ± 0.19 nmol L^{-1} in 1995 and 0.29 ± 0.10 nmol L^{-1} in 1997. However, the mean u_{10} for the central Arabian Sea during the 1995 SW monsoon (9.0 ± 3.0 m s^{-1}) was lower than in 1997 (12.2 ± 2.8 m s^{-1}), causing lower emission for 1995. The opposite trend was observed for the coastal upwelling region. The mean ΔC and u_{10} were higher in 1995 (8.9 ± 3.4 nmol L^{-1} and 12.3 ± 1.3 m s^{-1}) than in 1997 (5.8 ± 3.3 nmol L^{-1} and 9.8 ± 2.0 m s^{-1}), thus yielding considerably higher N_2O emissions for the coastal upwelling region in 1995.

The overall annual N_2O emissions are in the range from 0.16 to 0.31 Tg N_2O yr^{-1} (0.1–0.2 Tg N yr^{-1}), which is a factor of 4 lower than our previous estimate of 0.8–1.5 Tg N_2O yr^{-1} (0.5–1.0 Tg N yr^{-1}) [*Bange et al.*, 1996]. This considerable discrepancy results from the application of a different, more realistic area distribution for the regime classification which was established by *Körtzinger et al.* [1997]. Additionally, in this study we use a southern boundary of 6°N which consequently yields a reduction of the overall Arabian Sea area to 4.93 x 10^{12} m^2. It appears that in our previous estimate the area for coastal upwelling regions was considerably overestimated, thus causing an overrating of the N_2O emissions from the coastal upwelling area. Our reassessment is at the lower end of previous estimates (Table 4), which range from 0.2 to 1.0 Tg N_2O yr^{-1} (0.1–0.6 Tg N yr^{-1}) [*Lal and Patra*, 1998; *Law and Owens*, 1990; *Naqvi and Noronha*, 1991]. On the basis of the data listed in Table 4 we roughly estimated an annual N_2O flux to the atmosphere of ~0.4 Tg N_2O yr^{-1} (0.25 Tg N yr^{-1}). However, our estimate might be conservative since recent N_2O measurements in the upwelling region off southwestern India during the SW monsoon showed extremely high N_2O concentrations [*Naqvi et al.*, 1998], which may lead to an upward revision of the current estimates.

4.3. N Sedimentation

The total accumulation rates from *Sirocko et al.* [1991] and the measured nitrogen contents as listed in Table 5 were used to calculate a mean nitrogen accumulation rate of 52.8 ± 31.2 mg N m^{-2} yr^{-1}. The high accumulation rates found for the Oman Basin (cores KS8 and 422) seem to not be representative for the rest of the Arabian Sea; thus we did not use them for averaging. The high N sedimentation rates of the cores KS8 and 422 (which are located at the continental slopes) seem to be influenced by the high productivity of the continental margins of the western Arabian Sea. Since the data in Table 5 are from the deep-sea environment, we used a reduced area of 4.16 x 10^{12} m^2 (i.e., the area of Arabian Sea north of 6°N with water depths below 1000 m) for our extrapolation. The resulting annual N accumulation rate of ~0.22 Tg N is to be considered as a lower limit of the overall N accumulation in the Arabian Sea. The high sedimentation rates from the cores KS8 and 422 suggest that the overall N sedimentation might be considerably higher when data from the continental margins are included. A rough estimate based on the data from cores KS8 and 422 (Table 5) and by

Table 3. Mean N_2O Emissions From the Arabian Sea (north of 6°N) During 1995 and 1997

		1995		1997	
	Area, 10^{12} m^2	Flux density,[b,c] pmol m^{-2} s^{-1}	Emissions,[b] Tg N_2O $(0.5yr)^{-1}$	Flux density,[b] pmol m^{-2} s^{-1}	Emissions,[b] Tg N_2O $(0.5yr)^{-1}$
Intermonsoon					
Arabian Sea (central + upwelling)	4.93	3.8 / 6.2	0.01 / 0.02	4.0 / 7.1	0.01 / 0.02
SW monsoon					
Coastal upwelling	0.2[a]	731 / 1388	0.10 / 0.19	348 / 611	0.05 / 0.08
Filaments	0.5[a]	68 / 117	0.02 / 0.04	76 / 133	0.03 / 0.05
Central Arabian Sea	4.23	11 / 17	0.03 / 0.05	29 / 55	0.09 / 0.16
Sum = annual mean, Tg N_2O yr^{-1}			0.16 / 0.30		0.18 / 0.31
(Sum in Tg N yr^{-1})			(0.10 / 0.19)		(0.11 / 0.20)

[a] Data taken from *Körtzinger et al.* [1997] (central Arabian Sea includes the Gulf of Oman).
[b] First value calculated according to *Liss and Merlivat* [1986]; second value calculated according to *Wanninkhof* [1992].
[c] Data taken from *Bange et al.* [1996].

Table 4. Overview of N_2O Emission Estimates for the Arabian Sea

Arabian Sea Region	Date	Area Used for Extrapolation, 10^{12} m^2	Range, Tg N_2O yr^{-1}	Mean, Tg N_2O yr^{-1}	References
Central/west	May and July–Aug. 1995 March and May–July 1997	4.93	0.16–0.31	0.2	this study, see Table 3
Central/west/Gulf of Oman	Sep.–Oct. 1986	1.56	0.22–0.39[a]		*Law and Owens* [1991]
Central/west/Gulf of Oman	Aug.–Oct. and Nov.–Dec. 1994	8.0	(0.41–0.75)[e]		*Upstill-Goddard et al.* [1999]
Central/east	April–May 1994 Feb.–March and July–Aug. 1995 Aug. 1996	6.23	0.56–1.0	0.6[d]	*Lal and Patra* [1998]
Central/east	Dec. 1988	6.23	0.44–0.83[b]	0.5[d]	*Naqvi and Noronha* [1991]
Somali Basin	July–Aug. 1992	0.84	0.03–0.05[c]		*De Wilde and Helder* [1997]
Average				0.4	

[a] Not used for averaging because range is only valid for the upwelling region.

[b] Original value of 0.44 Tg N_2O yr^{-1} was multiplied by a factor of 1.9 to yield a range for better comparison owing to different air–sea exchange models used.

[c] Not used for averaging because range is only valid for the Somali Basin for a period of two months.

[d] Data were scaled down to the area of the Arabian Sea north of 6°N (4.93 x 10^{12} m^2) by multiplying with 0.79 (i.e., 4.93/6.23).

[e] Not used for averaging because range represents semiannual estimates.

applying an area of 0.77 x 10^{12} m^2 (i.e., the area of Arabian Sea north of 6°N with water depths above 1000 m) yields a N sedimentation of 0.26 Tg N yr^{-1}. However, since representative data are missing, an assessment of the contribution by the shelf area remain highly speculative.

5. Discussion

Sedimentary denitrification will be most significant for the highly productive shelf areas along the Indian coast and the coast of the Arabian Peninsula. Unfortunately, measurements of denitrification in the Arabian Sea sediments are not available. Following the approach of *Seitzinger and Giblin* [1996], we estimated the amount of the sedimentary N loss, based on their empirical relationship which couples the primary production rates to the sedimentary denitrification rate:

$$DNF_c = 0.019\ PP,$$

where PP stands for the depth-integrated primary production in

Table 5. Overview of the Mass Accumulation Rates, Total Nitrogen, and the Calculated N Deposition Rates From Various Sediment Cores of the Arabian Sea North of 6°N

	Latitude,[a] °N	Longitude,[a] °E	Water depth,[a] m	AR,[a] g m^{-2} yr^{-1}	TN, %	Flux, mg N m^{-2} yr^{-1}
Arabian Basin						
15KI	14.88	64.74	3920	23.32	0.07	16.3
36KL	17.07	69.04	2055	18.50	0.05	9.3
51KL	20.96	65.55	2644	39.50	0.10	39.5
57KL	20.90	63.12	3422	38.50	0.16	61.6
71KL	16.23	60.25	4029	33.82	0.20	67.6
74KL	14.32	57.34	3212	70.33	0.18	126.6
82KL	12.68	58.67	4416	49.22	0.11	54.1
87KL	10.50	57.73	3773	58.25	0.06	35.6
232SK	21.78	64.60	3098	52.50	0.11	57.8
182SK	8.77	73.70	2234	22.41	0.12	26.9
Somali Basin						
105KK	11.25	53.54	3535	54.00	0.12	64.8
114KK	8.00	51.21	3843	61.52	0.12	73.8
Oman Basin						
KS8	23.46	59.19	2900	150.08	0.20	300.2[b]
422	24.39	59.04	2732	141.75	0.26	368.6[b]
Average ± sd						52.8 ± 31.2

AR, accumulation rates; TN, total nitrogen; sd, standard deviation.

[a] Data from *Sirocko et al.* [1991].

[b] Not used for averaging (see text for details).

mmol C m^{-2} d^{-1} and DNF_c is the resulting denitrification in mmol N m^{-2} d^{-1}. Primary production in the shelf areas along the coast of India shows values from less than 1000 mg C m^{-2} d^{-1} (NE monsoon) up to 6000 mg C m^{-2} d^{-1} (SW monsoon) (S.W.A. Naqvi, personal communication, 1999). At the shelf off Oman, primary production ranges from 1024 mg C m^{-2} d^{-1} (fall intermonsoon, November 1994, [*Watts et al.*, 1999]) to 3818 mg C m^{-2} d^{-1} (SW monsoon, August–September1994 [*Watts et al*, 1999]). The shelf (0–200 m) covers ~10% of the Arabian Sea area north of 6°N (0.51 x 10^{12} m^2). Taking 1000 and 3000 mg C m^{-2} d^{-1} as averages for PP during the intermonsoon and SW monsoon, respectively, and assuming that the SW monsoon lasts for 120 days (from late May to September), we estimated a seasonally weighted annual N loss due to sedimentary denitrification of ~6.8 Tg N.

N fixation data from the Arabian Sea are rare and difficult to compare owing to the different assumptions and methods applied. *Somasundar et al.* [1990] estimated an annual N fixation of 1.5 Tg N by assuming a four-month occurrence of the N-fixing cyanobacterium *Trichodesmium* in an area of 0.3 x 10^{12} m^2. Recent measurements of N fixation rates of *Trichodesmium* during M32/3 (May 1995) were extrapolated to a seasonal-weighted N fixation of 1 Tg N yr^{-1} for a total Arabian Sea area of 7 x 10^{12} m^2 [*Capone et al.*, 1998]. By scaling down *Capone et al.*'s [1998] estimate to the area of 4.93 x 10^{12} m^2 for the Arabian Sea north of 6°N we obtain an annual N fixation of 0.6 Tg N yr^{-1}. This is at the low end of the range of 1 to 6 Tg N yr^{-1} (average 3.5 Tg N yr^{-1}) estimated by *Brandes et al.* [1998] for an area of 1.2 x 10^{12} m^2 in the central Arabian Sea. *Brandes et al.* [1998] based their estimate on the assumption that the observed N isotope signature of NO_3^- in the surface results from N fixation. Thus an annual estimate for N fixation in the Arabian Sea might range from 0.6 to 6 Tg N (average 3.3 Tg N yr^{-1}). However, we caution that our estimate is associated with a high degree of uncertainty. For comparison we scaled up *Brandes et al.*'s [1998] estimate, yielding a N fixation in the range from 4.1 to 24.7 Tg N yr^{-1} (average 14.4 Tg N yr^{-1}). However, since the estimate by *Brandes et al.* [1998] is based on data from the central Arabian Sea, where N fixation is most probably more pronounced than in the NO_3^- rich upwelling areas, where N fixation can be assumed to be negligible, an upscaling of their values to the total Arabian Sea area seems to yield unrealistic high results.

N supply through advection and diffusion from south of the Arabian Sea was first proposed by *Naqvi et al.* [1992]. In order to assess the mean annual N exchange across the southern boundary of the Arabian Sea at 6°N, monthly values for the water transport across 6°N were extracted from a general circulation model (GCM) consisting of 13 depth layers with a 1° x 1° horizontal resolution [*Drijfhout et al.*, 1996, E. Maier-Reimer, personal communication, 1999]. On the basis of the monthly values, we calculated annual means for each of the 403 grid points along 6°N. NO_3^- values were taken from the NO_3^- data of *Conkright et al.* [1994] (hereinafter referred to as WOA94), which contains fields of annual mean NO_3^- data for 33 standard depth levels with a 1°x1° horizontal resolution. The extracted NO_3^- were scaled to the grid points of the GCM. Then we calculated for each grid point the mean annual N flux. Summarizing the fluxes yields the net N fluxes for each layer (Figure 6). The major N fluxes are located in the depth layers from 90 to 3000 m resulting in an annual net N input of 25 Tg N (66%). The N input through the deep layers below 3000 m represents ~7 Tg N yr^{-1} (18%), which is comparable with the net N input of 6 Tg N yr^{-1} (16%) for the surface layers (0–90 m). The resulting overall net flux sums up to an annual input into the Arabian Sea of ~38 Tg N a^{-1}. However, the extracted NO_3^- atlas data appear to be biased by low concentrations in the intermediate and deep layers. A cross check of the NO_3^- data from the WOA94 with recent NO_3^- measurements at 6°N, 65°E in July 1995 indicated that the atlas values below 800 m are ~3 μmol L^{-1} lower than the measured values (Figure 6a). Applying the described procedure to the measured NO_3^- profile instead of the atlas data yielded a reduced overall net N flux of 31 Tg N yr^{-1}, indicating a possible overestimation of the N flux when the atlas NO_3^- data are used.

In Table 6 we present a list of the N fluxes to and out of the Arabian Sea as discussed in the sections 3 – 5 together with previous compilations of N fluxes. Unfortunately, benthic N fixation fluxes are not known for the Arabian Sea. We calculated a slight surplus of ~5 Tg N yr^{-1}. However, in view of the considerable uncertainties associated with the listed fluxes we conclude that the budget is reasonably balanced. The main difference between our estimate and *Naqvi et al.*'s [1992] estimate is that they computed a considerably higher N input by advection, which in turn is the reason for the unrealistic high N surplus of their budget. In comparison with *Naqvi et al.*'s [1992] estimate, our budget shows higher fluxes for N input by rivers, N fixation, N aerosol input, and sedimentary denitrification. An additional but minor difference is that we did not consider the N_2O loss within reducing zones, which appears to be overestimated [*Naqvi et al.*, 1992]. In contrast, *Somasundar et al.* [1990] suggested a very low pelagic denitrification of only 2.05 Tg N yr^{-1} which seem to be underestimated in view of recently published results [see list by *Howell et al.*, 1997]. Figure 7 gives a simplified overview of the overall N cycling in the Arabian Sea. Since the shelf areas of the Arabian Sea represent a typical "high N–low O_2" environment [*Middelburg et al.*, 1996], we assumed that the decomposition of particulate organic nitrogen (PON) during sedimentary denitrification is mainly fueled by diffusion of NO_3^- from the water column into the shelf sediments (Figure 7) [*Middelburg et al.*, 1996].

6. Internal N Cycling

Assuming that the flux of particulate organic nitrogen (PON) out of the photic zone (i.e., the export flux) balances the new production which in turn is equal to the NO_3^- uptake (i.e., the NO_3^- assimilation) in the photic zone, we can roughly estimate the export flux based on NO_3^- assimilation data. In a recent publication, *Watts et al.* [1999] report total N assimilation rates and integrated *f* ratios (here defined as the ratio of the NO_3^- assimilation to the total N assimilation in the photic zone) measured at 11 stations during the late SW monsoon (August–September 1994) and at 13 stations during the fall intermonsoon (November–December 1994) in the western (including the shelf area off Oman) and central Arabian Sea north of 7°N. On basis of the data by *Watts et al.* [1999], we roughly extrapolated an annual total N assimilation of ~181 Tg N (128 Tg N yr^{-1} excluding shelf) and an annual PON export flux of ~86 Tg N (49 Tg N yr^{-1} excluding shelf).

On the basis of the fluxes of PON at 3000-m depth [*Schäfer and Ittekkot*, 1995], we extrapolated the flux of PON which

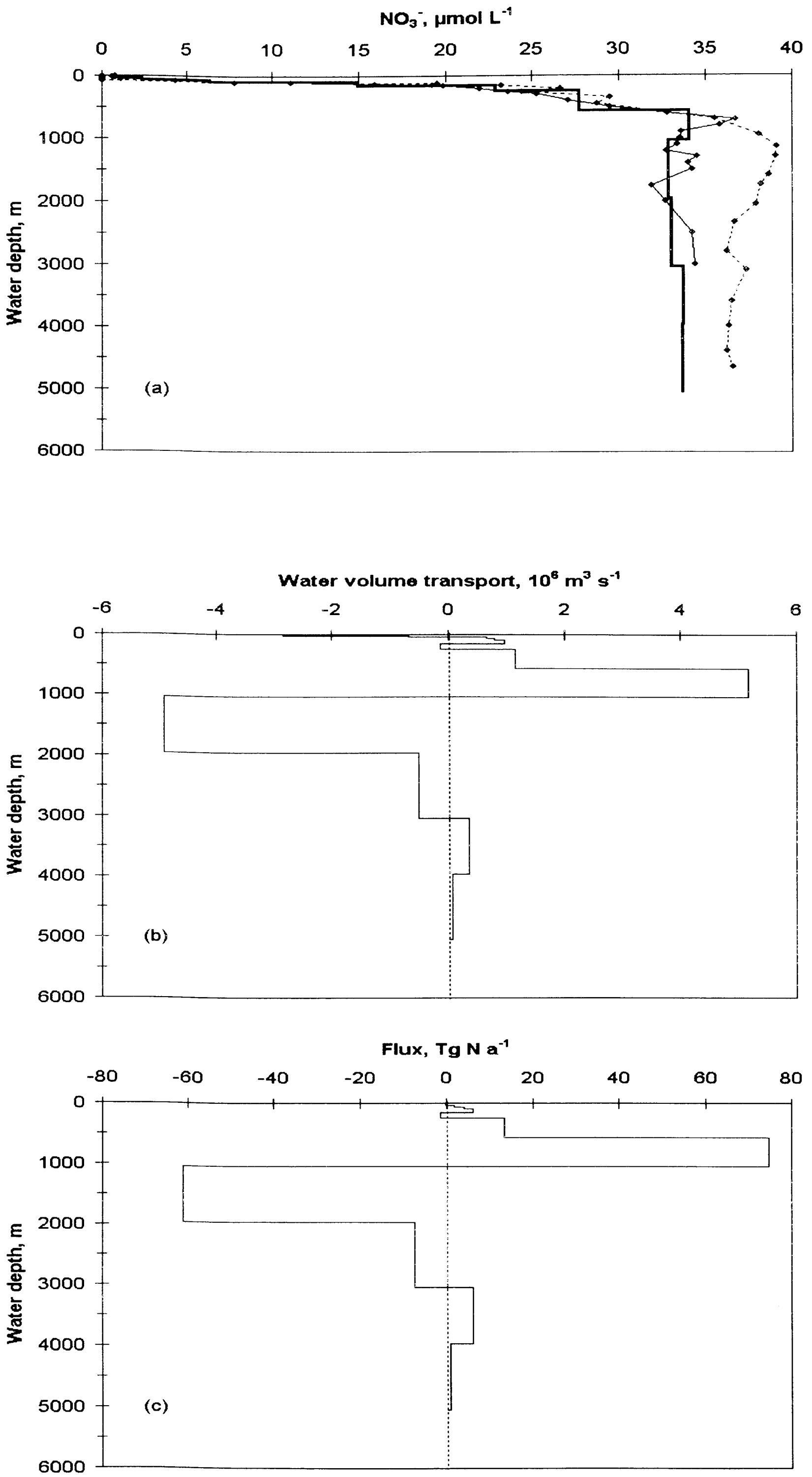

Figure 6. N flux into and out of the Arabian Sea along 6°N: (a) NO_3^- concentrations (thick solid line, overall mean annual NO_3^- extracted from the WOA94; dashed line, measured NO_3^- profile at 6°N, 65°E in July 1995 during cruise M32/5; thin solid line, standard level mean annual NO_3^- profile at 60.5°N, 65.5°E extracted from the WOA94). (b) Mean annual water volume transport for the GCM layers (negative values represent outflows and positive values represent inflows into the Arabian Sea across 6°N). (c) Resulting mean annual N flux for the layers of the GCM (negative values represent outflows and positive values represent inflows into the Arabian Sea across 6°N).

Table 6. Revised N Budget of the Arabian Sea (north of 6°N)

	This Study	S90	N92
Sources			
Atmospheric dry and wet depositions of NO_3^- and NH_4^+	1.6		0.7
Pelagic N fixation	3.3	1.5[d]	1.5
Input from marginal seas (Red Sea, Persian Gulf)	1.1[a]	1.6	1.1
Dissolved inorganic N input from rivers	1.2[b]	0.1	0.1
Northward transport	38		114
Sinks			
Pelagic denitrification	33	2.05	30
Sedimentary denitrification	6.8		1.0
N sedimentation	>0.22	0.17	0.2
N_2O loss to the atmosphere	0.25		0.3
N_2O loss in reducing zones			2.2
NH_3 loss to the atmosphere	0.05[c]		
Σ Sources – Σ Sinks	4.9	0.98	83.7

All fluxes are in Tg N yr^{-1} For comparison we listed previous N budgets compiled by *Somasundar et al.* [1990] (S90) and *Naqvi et al.* [1992] (N92).

[a] Taken from *Naqvi et al.* [1992].

[b] (S. Seitzinger and C. Kroeze, personal communication, 1999). Value was calculated with the model by *Seitzinger and Kroeze* [1998]. The Arabian Sea's southern boundary was set to the equator; however, significant riverine N inputs in the area from 0° to 6°N (i.e., the Somali coast) are unlikely because there are no major rivers.

[c] Extrapolated by using a NH_3 flux density of 25 pmol m^{-2} s^{-1} estimated as the mean of the median values reported for the central Arabian Sea (5–40 pmol m^{-2} s^{-1}) and the coastal area off Oman (15–40 pmol m^{-2} s^{-1}) by *Gibb et al.* [1999]. The applied area for the Arabian Sea north of 6°N was 4.93 x 10^{12} m^{12}.

[d] The original S90 budget included a particulate organic nitrogen flux of 5.04 Tg N yr^{-1} calculated for a depth of 1000 m instead of the N fixation flux. However, for better comparison we modified the S90 budget, since we consider the PON flux as part of the internal N cycling in the Arabian Sea.

reaches the deep sea to be ~1.2 Tg N yr^{-1}. That means that ~48 Tg N yr^{-1} (i.e., 49 – 1.2 Tg N yr^{-1}) are remineralized between the photic zone and 3000 m. Only 0.2 Tg N yr^{-1} (see Table 6) are buried in the deep-sea sediments, the rest is remineralized at the sediment–water interface. However, could the PON flux maintain the observed denitrification fluxes? *Gruber and Sarmiento* [1997] proposed the following equation for the remineralization of organic matter coupled to denitrification:

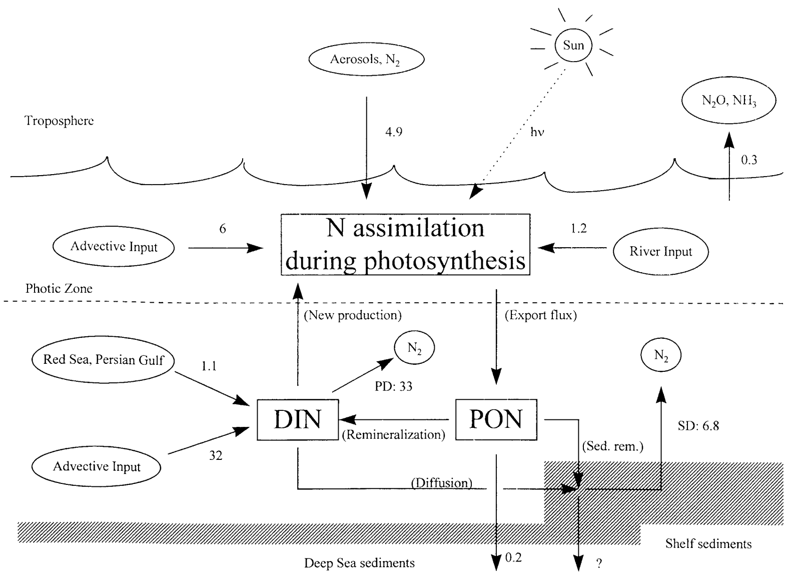

Figure 7. Simplified scheme of the N cycling in the Arabian Sea north of 6°N. All fluxes are given in Tg N yr^{-1} (see text and Table 6 for details). DIN stands for the sum of dissolved inorganic nitrogen, and PON stands for particulate organic nitrogen. The denitrification fluxes are abbreviated as follows: PD, pelagic denitrification and SD, sedimentary denitrification. The question mark stands for the unknown N burial rate at the shelf slope sediments. Sed. rem. stands for remineralization of PON in the shelf sediments.

$$C_{106}H_{175}O_{42}N_{16}P + 104\ NO_3^- \rightarrow$$
$$4\ CO_2 + 102\ HCO_3^- + 60\ N_2 + 36\ H_2O + HPO_4^{2-}.$$

According to this equation, 16 moles of PON and 104 moles of dissolved inorganic N are used to produce 120 moles N (i.e., in form of N_2). Consequently, we can estimate the amount of PON required to produce 39.8 Tg N yr^{-1} (i.e., the sum of pelagic and sedimentary denitrification). We estimated that ~5.3 Tg N yr^{-1} (i.e., 39.8 Tg N yr^{-1} x 16/120) as PON are required to maintain the observed denitrification fluxes. Comparing this value with the calculated overall PON export flux of 86 Tg N yr^{-1}, we conclude that there seems to be more than enough organic nitrogen available to support the observed rate of denitrification. In other words, sedimentary and pelagic denitrification together demand of ~6% of the estimated PON export flux from the photic zone.

N fixation and atmospheric deposition of N aerosols account for ~3.8 and 1.9% of the annual export flux or new production, respectively. However, a more detailed analysis revealed that there seem to be spatial and seasonal differences in the contribution of N aerosols to the N cycle in the Arabian Sea. In Table 7 we give some examples for the contribution of the dry deposition of NO_3^- and NH_4^+ to the new production in the oceanic surface layer at selected stations in the Arabian Sea. Obviously, atmospheric dry N deposition plays only a minor role for the N cycling in the Arabian Sea's surface layer because of the enormous NO_3^- enrichment due to upwelling events, which fuels the primary production in the surface layer during the SW monsoon. Only in the southern part of the central Arabian Sea, which is less influenced by the NO_3^- enrichment in the surface layer, there might be a significant contribution (10–17%) to new production by the atmospheric dry deposition of NO_3^- and NH_4^+, especially during the intermonsoon. Since the atmospheric depositions of N compounds to the Arabian Sea area are directly linked to anthropogenic activities such as agriculture or industry, we speculate that increasing agricultural and industrial activities might lead to higher atmospheric N depositions, which will mainly affect the N cycle in the central Arabian Sea.

7. Conclusions

On the basis of our scheme of the N cycling (Table 5 and Figure 7), we conclude that the N cycle in the Arabian Sea is dominated by only two processes (i.e., denitrification and advective N input from the south). The role of N fixation in the Arabian Sea is still difficult to assess owing to the small database available; however, there are hints that it might be more important than previously thought. Fluxes such as N input by rivers, marginal seas, and aerosols and N losses to the atmosphere as N_2O and NH_3 seem to be of minor or regional importance. Our main conclusions are as follows:

1. Beside the well-known pelagic denitrification, sedimentary denitrification is a further major N loss process in the Arabian Sea. As shown in section 5, the magnitude of the sedimentary denitrification might be ~6.8 Tg N yr^{-1}, representing ~17% of the total denitrification flux of ~39.8 Tg N yr^{-1}. Therefore we conclude that the shelf sediments of the Arabian Sea might be of considerably greater importance for the N cycling in the Arabian Sea than previously thought. Because flux measurements for sedimentary denitrification and N burial in shelf sediments are not available, the importance of the shelf areas for the N cycling in the Arabian Sea might have been overlooked in previous assessments.

2. The advective transport of NO_3^- into the Arabian Sea's intermediate layers from the south is the major N source. It supplies enough N to balance the N deficit as the result of the enormous denitrification rates. Our conclusion is partly in contrast to *Naqvi et al.* [1992], who suggested that the N deficit of the Arabian Sea is balanced by the N input through advection and subsequent upwelling of deep water below 4000 m. Instead, the N cycling appears to be closely linked to the circulation of the intermediate water masses in the depth range of 250–2000 m (Figure 6). Main source water masses entering the Arabian Sea intermediate layers from the south are the Indian Central Water (ICW) and the North ICW originating from the southern Indian Ocean and the Bay of Bengal, respectively [*You,* 1997]. Thus any

Table 7. Nitrogen Dry Deposition and its Contribution to New Production at Selected Stations in the Arabian Sea

	Aerosol Concentration, ng N m^{-3}	Deposition,[a] mg N m^{-2} d^{-1}	Aerosol NP,[b] mg C m^{-2} d^{-1}	PP, mg C m^{-2} d^{-1}	*f* ratio[c]	NP,[d] mg C m^{-2} d^{-1}	Aerosol NP / NP, %
May 1995							
18°N, 65°E	301 / 278	0.39 / 0.01	3.0 / 0.09	250	0.20	50.9	6.0
10°N, 65°E	363 / 180	0.47 / 0.01	3.6 / 0.06	160	0.14	21.8	16.7
July–Aug. 1995							
18.5°N, 57.3°N	145 / 30	0.19 / 0.01	1.4 / 0.01	3340	0.96[e]	3206	0.04
06°N, 65°E	78 / 19	0.10 / 0.001	0.8 / 0.01	920	0.51	467	0.2
March 1997							
18°N, 65°E	289 / 612	0.37 / 0.03	2.8 / 0.20	814	0.48	393	0.8
06°N, 65°E	218 / 520	0.28 / 0.02	2.1 / 0.170	164	0.14	22.8	10.1

NP, new production; PP, primary production. In columns 2–4 the first value refers to NO_3^- and the second value refers to NH_4^+.

[a] Applied deposition velocities are 1.5 and 0.05 cm s^{-1} for NO_3^- and NH_4^+, respectively [*Schäfer et al.*, 1993].

[b] Aerosol derived new production calculated from the aerosol deposition with a C:N ratio of 125.2:14.2 [*Millero et al.*, 1998].

[c] The *f* ratio was calculated as $PP/400 - PP^2/340{,}000$; PP stands for primary production in g C m^{-2} yr^{-1} [*Berger et al.*, 1989].

[d] Primary production derived new production calculated as *f* ratio times primary production.

[e] The *f* ratio was adopted from *Watts et al.* [1999] since the equation by *Berger et al.* [1989] (see footnote c) is only valid for primary production up to 1370 mg C m^{-2} d^{-1} (i.e., 500 g C m^{-2} yr^{-1}).

changes in the intermediate water circulation of the Indian Ocean will influence the N cycling in the Arabian Sea [*Rixen et al.*, 1996]. Two scenarios are possible: First, a decreased inflow of intermediate waters will result in a decreased N supply and a longer residence time of the intermediate waters in the Arabian Sea. This in turn might lead to enhanced denitrification rates favored by the reduced ventilation. Consequently, because of the continuous N loss via denitrification, the Arabian Sea might be driven to a N limited system. This in turn might result in a considerable enhancement of the N fixation as an alternative N source. Moreover, atmospheric deposition of N aerosols will become more important as an additional N source. Second, an increased inflow of intermediate waters will result in a shorter residence time of the intermediate waters in the Arabian Sea. This will lead to increasing oxygen concentrations, which in turn might cause a reduced N loss via denitrification in the intermediate layers. However, this will not necessarily result in a continuous enhancement of the N assimilation in the surface layer since the availability of other nutrients such as iron might become the limiting factor for the biological productivity. Changes of the Indian Ocean intermediate circulation pattern due to global change might be likely [*Schulte et al.*, 1999]; however, since the circulation patterns are still associated with considerable uncertainties, future prediction would be speculative.

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