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▶ To cite this version:

S. Walter, H. W. Bange, U. Breitenbach, D. W. R. Wallace. Nitrous oxide in the North Atlantic Ocean. Biogeosciences Discussions, 2006, 3 (4), pp.993-1022. hal-00297832

HAL Id: hal-00297832 https://hal.science/hal-00297832

Submitted on 18 Jun 2008

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Nitrous oxide in the North Atlantic Ocean

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Received: 2 May 2006 - Accepted: 8 May 2006 - Published: 17 July 2006

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Abstract

In order to investigate the role of the North Atlantic Ocean as a source of atmospheric nitrous oxide and to decipher the major formation pathways of nitrous oxide, measurements of dissolved nitrous oxide were made during three cruises in the tropical,

- ⁵ subtropical and subpolar North Atlantic in October/November 2002, March/April 2004, and May 2002, respectively. Nitrous oxide was close to equilibrium or slightly supersaturated in the surface layers suggesting that the North Atlantic acts as a weak source of nitrous oxide to the atmosphere. Depth profiles showed supersaturation throughout the water column with a distinct increasing trend from the subpolar to the tropical supersaturation.
- ¹⁰ region. Lowest nitrous oxide concentrations, near equilibrium and with an average of 11.0 ± 1.7 nmol L⁻¹, were found in the subpolar North Atlantic where the profiles showed no clear maxima. Highest values up to 37.3 nmol L⁻¹ occurred in the tropical North Atlantic with clear maxima at approximately 400 m. A positive correlation of nitrous oxide with nitrate, as well as excess nitrous oxide with AOU, was only observed in the sub-
- tropical and tropical regions. Therefore, we conclude that the formation of nitrous oxide occurs in the tropical region rather than in the subpolar region of the North Atlantic and suggest nitrification is the dominant formation pathway in the subtropical and tropical regions.

1 Introduction

Nitrous oxide (N₂O) is an important atmospheric trace gas due to its influence on the Earth's climate. In the troposphere N₂O acts as a greenhouse gas whereas in the stratosphere it is involved in the depletion of ozone by providing NO-radicals (Prather et al., 2001). Since the beginning of the industrial revolution the global mean tropospheric N₂O mole fraction has risen rapidly from 270 ppb up to 314 ppb in 1998
 (Prather et al., 2001). About 24% of the natural sources of atmospheric N₂O are contributed by the oceans (Prather et al., 2001; Seitzinger et al., 2000). Nitrous oxide is

BGD 3, 993-1022, 2006 Nitrous oxide in the North Atlantic Ocean S. Walter et al. **Title Page** Abstract Introduction Conclusions References **Figures** Tables 14 Back Close Full Screen / Esc **Printer-friendly Version** Interactive Discussion EGU

an important component of the oceanic nitrogen cycle, mainly formed by the microbial processes of nitrification and denitrification (Codispoti et al., 2001; Goreau et al., 1980): Nitrification is an aerobic two-step process in which ammonium is oxidized to nitrate (NH⁺₄→NH₂OH→NO⁻₂→NO⁻₃) by two different groups of bacteria. In this process nitrous oxide is assumed to be a by-product, however until now the exact pathway for N₂O production remains unclear. In suboxic habitats nitrate can be reduced by denitrification to molecular nitrogen (NO⁻₃→NO⁻₂→NO→N₂O→N₂O), here nitrous oxide is an intermediate product. Especially at oxic/suboxic boundaries N₂O is produced by coupled nitrification and denitrification, due to the transfer of common intermediates (Yoshinari et al., 1997). Another possibility is aerobic denitrification, whereby under fully aerobic conditions organisms convert ammonia into nitrogen gas without the intermediary accumulation of nitrite (Robertson et al., 1988). All processes depend on

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termediary accumulation of nitrite (Robertson et al., 1988). All processes depend on oxygen concentrations, as well as the availability of substrates such as ammonium and nitrate. Many organisms are able to switch between different pathways depending on environmental conditions, and also the yield of N_2O during a process depends on environmental conditions (Goreau et al., 1980; Poth and Focht, 1985; Richardson, 2000). Positive correlations of N_2O with apparent oxygen utilization (AOU) or nitrate are interpreted as production of nitrous oxide by nitrification (Yoshinari, 1976; Cohen and Gordon, 1978; Yoshida et al., 1989). However, up to now the dominant production pathway for N_2O on the global scale and the contribution of different pathways still remains unclear (Codispoti et al., 2001; Popp et al., 2002). Information on the vertical N_2O distribution in the North Atlantic is sparse, only a few

²⁵ et al. (1995), and recently data from a transect at 7°30′ N were reported by Oudot et al. (2002). In this paper we present a comprehensive set of 73 vertical profiles of nitrous oxide from three trans-Atlantic cruises, covering the subpolar North Atlantic, the subtropical and the tropical North Atlantic. Based on these new data, we examine the regional differences of the N₂O distribution and its formation pathways.



2 Study area

2.1 Research cruises

Samples from the three cruises were collected over the period from May 2002 to April 2004 (see Fig. 1).

⁵ The first cruise (May/June 2002), started in Hamburg, Germany with the German research vessel "Gauss". The cruise track followed the WOCE-A2 transect to Halifax, Canada. Depth profiles of N₂O were measured at 16 stations. The WOCE-A2 transect is located between 42° N and 49° N.

The subtropical North Atlantic was investigated during March/April 2004 onboard the research vessel "Meteor". The cruise started in Fort de France, Martinique (French Antilles) in the western part of the Atlantic and ended in Lisbon (Portugal). Samples were taken at 37 stations. Most stations were co-located with stations where samples were taken during the Transient Tracers in the Ocean Program (TTO) in 1982.

- The tropical North Atlantic samples were taken during the M55-SOLAS cruise (Wallace and Bange, 2004) in October/November 2002, again with the German research vessel "Meteor". This cruise started in the western tropical North Atlantic in Willemstad, Curaçao (Netherlands Antilles) and followed a cruise track along 10–11° N to Douala (Cameroon). The track included a transect to the equator between 26° W and 23.5° W. N₂O profiles were taken at 20 stations.
- 20 2.2 Hydrography

Several water masses in the North Atlantic can be identified in the T-S-diagram based on data from the three cruises (see Fig. 2). The main Atlantic water masses were identified according to commonly used classification schemes (Tomczak, 1999; Alvarez et al., 2004; Aiken et al., 2000; Joyce et al., 2001; Poole and Tomczak, 1999).

²⁵ The WOCE A2 transect (Gauss 384-1 cruise), is located at the boundary region between the subpolar gyre (Gordon, 1986) and the subtropical gyre (Krauss, 1996). This

BGD						
3, 993–1	3, 993–1022, 2006					
Nitrous oxide in the North Atlantic Ocean						
S. Wal	S. Walter et al.					
Title	Page					
Abstract	Introduction					
Conclusions	References					
Tables	Figures					
14	►I					
•	•					
Back	Close					
Full Scr	Full Screen / Esc					
Printer-frie	Printer-friendly Version					
Interactive	Interactive Discussion					
EGU						

region is highly variable, characterized by the exchange of upper-ocean water between the gyres mainly via the North Atlantic Current, and the Labrador Current. One of the most important water masses here is the Labrador Sea Water (LSW). These water masses provide the major part of the North Atlantic Intermediate Water in combination

- with the outflow of Mediterranean Sea Water (MW), which is detected in the eastern basin of the subtropical Atlantic Ocean near the Strait of Gibraltar (Richardson et al., 2000) and the Antarctic Intermediate Water (AAIW) from the south (Lorbacher, 2000). Additional water masses of the southern hemisphere that penetrate into the North Atlantic are the South Atlantic Central Water (SACW) and the Antarctic Bottom Water (AABW). SACW flows northwards, and mixes with the North Atlantic Central Water (NACW) at approximately 15° N in the western and 20° N in the eastern basin (Poole
 - and Tomczak, 1999; Aiken et al., 2000).

A typical freshwater influence was found during the Meteor 55 cruise in the western tropical North Atlantic. Water of the Amazon was detected in the surface water, identi-

¹⁵ fied by high temperatures and low salinity. These plumes of freshwater are transported northwards by the North Brazil Current and eastwards by the equatorial current system (Fratantoni and Glickson, 2002).

3 Material and methods

Water samples for N₂O analysis were collected in triplicate from various depths, taken with a 24-Niskin-bottle rosette, equipped with a CTD-sensor. The analytical method applied is a modification of the method described by (Bange et al., 2001). Bubble free samples were taken immediately following oxygen sampling in 24 mL glass vials, sealed directly with butyl rubber stoppers and crimped with aluminium caps. To prevent microbial activity, samples were poisoned with 500 μ L of 2 mM mercury chloride solution. Then 10 mL of sample was replaced with a helium headspace for each vial,

and the samples were allowed to equilibrate for at least two hours at room temperature (temperature was recorded continuously). A 9 mL subsample from the headspace



was used to flush a 2mL sample loop after passing through a moisture trap (filled with Sicapent[®], Merck Germany). Gaschromatographic separation was performed at 190° C on a packed molecular sieve column (6ft×1/8″ SS, 5A, mesh 80/100, Alltech GmbH, Germany). The N₂O was detected with an electron capture detector. A
⁵ mixture of argon with 5% by volume methane was used as carrier gas with a flow of 21 mL min⁻¹. For the two-point calibration procedure we used standard gas mixtures with 311.8 ±0.2 ppb and 346.5 ±0.2 ppb N₂O in synthetic air (Deuste Steininger GmbH, Mühlhausen Germany). The standard mixtures have been calibrated against the NOAA (National Oceanic and Atmospheric Administration, Boulder, Co.) standard scale in the laboratories of the Air Chemistry Division of the Max Planck Institute for Chemistry, Mainz, Germany.

3.1 Calculations

 N_2O water concentrations (C_{N2O}) were calculated as follows:

$$C_{N2O}\left[nmol L^{-1}\right] = \left(\beta x P V_{wp} + \frac{xP}{RTV_{hs}}\right) V_{wp}$$
(1)

¹⁵ where β stands for the Bunsen solubility in nmol L⁻¹ atm⁻¹ (Weiss and Price, 1980), *x* is the dry gas mole fraction of N₂O in the headspace in ppb, *P* is the atmospheric pressure in atm, V_{wp} and V_{hs} stand for the volumes of the water and headspace phases, respectively. *R* is the gas constant (8.2054×10⁻² L atm mol⁻¹ K^{-1}) and *T* is the temperature during equilibration. The salinity was measured by the CTD-Sensor during water sample collection. The overall relative mean analytical error was estimated to be ±1.8%.

The excess N_2O (ΔN_2O) was calculated as the difference between the calculated N_2O equilibrium concentration and the measured concentration of N_2O as follows

 $\Delta N_2 O[nmolL^{-1}] = N_2 O(observed) - N_2 O(equilibrium).$



(2)

To calculate the N₂O equilibrium concentration we used three different atmospheric mole fractions. Between the mixed layer and the atmosphere, N₂O exchanges in about three weeks (Najjar, 1992), thus we calculated ΔN_2 O in the mixed layer using the actual atmospheric N₂O value of 318 ppb measured during the "Meteor 55" cruise (Walter et al., 2004). Below the thermocline, exchange with the atmosphere is unlikely, thus, calculated N₂O equilibrium concentrations depend on the atmospheric N₂O mole fraction at the time of deep-water formation. However, the exact atmospheric mole fraction of N₂O during deep-water formation is unknown because of uncertainty in age determination of water masses. Generally, tropical Atlantic deep waters below 2000 m seem to be older than 200 years (Broecker and Peng, 2000). Therefore for depths >2000 m ΔN_2 O was calculated with the tropospheric preindustrial value of 270 ppb (Flückiger et al., 1999). An average of the actual and the preindustrial atmospheric value (i.e., 294 ppb) was used for the depth range between the upper thermocline and 2000 m. The thermocline was defined as the depth where the temperature differs from the sur-

- face temperature by more than 0.5°C (Tomczak and Godfrey, 2001). For the subtropical and subpolar region we calculated $\Delta N_2 O$ with these same mole fractions, although the age of water masses is different to the tropical Atlantic and therefore some values may be underestimated, whereas others may be overestimated. The resulting uncertainties of $\Delta N_2 O$ are about 10–15%; however, our conclusions are not significantly affected by
- this uncertainty. The equilibrium values of dissolved oxygen (O_2) were calculated with the equation given by Weiss (1970).

The apparent oxygen utilization (AOU) was calculated as followed:

AOU[μ mol L⁻¹]=O₂(equilibrium)-O₂(observed).



(3)

4 Results

- 4.1 Distribution of nitrous oxide in the North Atlantic
- 4.1.1 N₂O distribution along isopycnal levels

In the surface layer of the North Atlantic (Fig. 3a) N₂O concentrations were relatively
 uniform with 8.5±1.2 nmol L⁻¹. In the region of the Labrador Current N₂O concentrations were enhanced with an average of 11.6±0.9 nmol L⁻¹. During the "Meteor 55" cruise, a plume of Amazon Water had been identified in the western basin of the tropical North Atlantic (Körtzinger, 2003). In contrast to Oudot et al. (2002), who reported enhanced values in the plume of the Amazon River, we found no influence on N₂O concentrations (Walter et al., 2004).

Below the thermocline, N₂O concentrations were variable with respect to depths and regions. We found highest concentrations in the eastern basin of the tropical North Atlantic throughout the water column, with maximum concentrations on σ_{θ} surfaces between 26.3 and 27.1 (Figs. 3b–e). At the Midatlantic Ridge, located at approximately 10° W a distinct house on the water and eastern Atlantic house of the surfaces.

- ¹⁵ 40° W, a distinct boundary between the western and eastern Atlantic basins was observed (Figs. 3d–e). In the eastern subtropical North Atlantic, at approximately 1000 m (σ_{θ} 27.6–27.7), a tongue of outflow water from the Mediterranean Sea was detected by higher values of salinity and temperature (Richardson et al., 2000). However, we found no apparent influence of the Mediterranean water on N₂O concentrations.
- Like the surface layer, deep waters (Fig. 3f) showed nearly uniform N₂O concentrations, though with higher values of 13.3 ± 1.6 nmol L⁻¹. However, a weak but distinct trend of decreasing concentrations from the tropics (13.1 ± 1.3 nmol L⁻¹) to the subpolar North Atlantic (11.1 ± 1.4 nmol L⁻¹) could be observed.

BGD 3, 993-1022, 2006 Nitrous oxide in the North Atlantic Ocean S. Walter et al. **Title Page** Abstract Introduction Conclusions References **Figures** Tables 14 Back Close Full Screen / Esc **Printer-friendly Version** Interactive Discussion EGU

The vertical distribution of N_2O showed characteristically different profiles in different regions of the North Atlantic (Figs. 4a–c), and between the western and eastern basins of these regions (Figs. 5a–c).

⁵ In the subpolar North Atlantic (Fig. 4a) vertical gradients of nitrous oxide were weak over the complete cruise track, with no clear or only a very weakly pronounced subsurface maximum. N₂O concentrations were near equilibrium (11.0±1.3 nmol L⁻¹) throughout the water column, with average concentrations of 8.6±1.4 nmol L⁻¹ in the surface layer (σ_{θ} 25.3–27.0) and 11.3±1.5 nmol L⁻¹ below the thermocline down to the bottom (σ_{θ} 26.2–27.7). No differences between the western and the eastern basin were found (Fig. 5a).

In contrast, N₂O distributions and profiles in both the subtropical and tropical North Atlantic showed strong variations with water depth (Figs. 4b–c, Figs. 5b–c). In both regions, the profiles generally had one distinct maximum. In the surface layer (σ_{θ} 19.3–

¹⁵ 26.8) concentrations were uniform, increasing below the thermocline up to a maximum and decreasing down to approximately 2000 m (σ_{θ} 22.1–27.8). Below 2000 m (σ_{θ} 27.8– 27.9) N₂O concentrations were nearly constant with depth in both basins.

In the subtropical North Atlantic (Fig. 4b) N_2O surface concentrations were 8.7 ± 0.7 nmol L⁻¹, comparable to those in the subpolar North Atlantic. Maximum values using found at doubte between 600 to 1000 m (z = 00.7 a) using the subpolar North Atlantic.

²⁰ ues were found at depths between 600 to 1000 m (σ_{θ} 26.7–27.7); values ranged from 14.0 in the eastern basin (#198) to 21.3 nmol L⁻¹ in the western basin (#156). Below 2000 m (σ_{θ} >27.8), concentrations were nearly constant at 13.1±0.9 nmol L⁻¹. Profiles in the western subtropical North Atlantic showed distinct maxima, while in the eastern basin no clear maximum was expressed (Fig. 5b). From the western to the eastern basin maximum concentrations decreased slightly from 17.7±1.4 nmol L⁻¹ to 15.1±0.7 nmol L⁻¹. East of the Midatlantic Ridge maxima were not clearly expressed and were broader. Additionally, maximum ΔN_2O values were lower in the eastern (5.5±0.6 nmol L⁻¹) than in the western basin (7.9±1.3 nmol L⁻¹).

BGD 3, 993-1022, 2006 Nitrous oxide in the North Atlantic Ocean S. Walter et al. **Title Page** Abstract Introduction Conclusions References **Figures Tables** Back Close

EGU

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

In the tropical North Atlantic (Fig. 4c) surface concentrations, with an average of 7.4 ± 1.1 nmol L⁻¹, were slightly lower than in the subtropical and subpolar North Atlantic. In contrast to the subtropical North Atlantic, maxima of N₂O concentrations were found at shallower depths of approximately 400 m (σ_{θ} 26.8–27.1). The maximum values were higher in general, and ranged from 23.8 nmol L⁻¹ in the western basin (#4) to 32.1 nmol L⁻¹ in the eastern basin (#44). At station #36, located in the Guinea Dome area (Siedler et al., 1992; Snowden and Molinari, 2003), we observed the highest N₂O values of about 37.3 nmol L⁻¹ at 400 m (σ_{θ} 27.0) (Fig. 4c). At the equatorial stations the N₂O maxima were found at shallower water depths (240 m to 280 m, σ_{θ}

- ¹⁰ 26.6–27.0). Maximum values ranged from 22.3 nmol L⁻¹ (#26) to 24.9 nmol L⁻¹ (#24). Below 2000 m (σ_{θ} >27.8) concentrations in the tropical North Atlantic were similar to those in the subtropics with an average of 13.2 ± 1.3 nmol L⁻¹. In both basins of the tropical North Atlantic profiles looked similar with sharp and clear maxima, however, concentrations throughout the water column increased from west to east (Fig. 5c). Be-
- ¹⁵ low 2000 m (σ_{θ} >27.8) N₂O concentrations were about 2 nmol L⁻¹ higher in the eastern than in the western basin, whereas the difference of the maximum values was even higher (approximately 8 nmol L⁻¹).

 N_2O profiles of the subtropical and tropical North Atlantic are in good agreement, both in absolute concentrations and shape of profiles, with those measured during the

- ²⁰ Bromine Latitudinal Air/Sea Transect II (BLAST II) cruise in October/November 1994 (Butler et al., 1995, http://www.cmdl.noaa.gov/hats/ocean/blast2/blastii.html). Below 1500 m in the North Atlantic as far as 20° S, the mean N₂O concentration observed by Butler et al. (1995) was about 13.5±1.0 nmol L⁻¹ (n=18) which is in good agreement with our measurements (12.6±1.5 nmol L⁻¹, n=449).
- 25 4.2 Comparison of nitrous oxide with other parameters

Parameters most relevant for comparison with nitrous oxide are those assumed to be directly in connection with production pathways of N_2O , like oxygen or the apparent



oxygen utilization (AOU), and nitrate. In general, we found the excess of N_2O (ΔN_2O) positively correlated with AOU and nitrate (Fig. 6). However, in view of differences between the basins, these correlations might not be sufficient and need higher resolution. Therefore data were divided as shown in Fig. 7.

In Figs. 7a–f correlations between the excess of N_2O with AOU (Figs. 7a–c) and with NO_3^- (Figs. 7d–f) are divided for all data of the respective regions.

Since a multiple regression analysis turned out to be not applicable due to the colinearity between the independent variables nitrate and AOU, we applied simple regression analysis for the isopycnal levels below the thermocline (see Table 1). Above the thermocline in the surface layer no correlations were found.

In the subpolar North Atlantic (Figs. 7a, d) $\Delta N_2 O$ is low, with values near zero. There were no significant correlations found with AOU (Fig. 7a) or nitrate (Fig. 7d; see Table 1).

In the subtropical North Atlantic (Figs. 7b, e) $\Delta N_2 O$ was also low with values ranging from 0 to 10 nmol L⁻¹. In contrast to the subpolar North Atlantic we found significant

- ¹⁵ from 0 to 10 nmol L⁻¹. In contrast to the subpolar North Atlantic we found significant correlations between $\Delta N_2 O$, AOU (Fig. 7b) and nitrate (Fig. 7e; see Table 1), especially at depths down to the N₂O maxima (ca. 1000 m; σ_{θ} <27.7; see regression lines in Figs. 7b, e). Below 1000 m (σ_{θ} 27.7) $\Delta N_2 O$ did not correlate with AOU or NO₃⁻ (circled data in Figs. 7b, e).
- ²⁰ In the tropical North Atlantic (Figs. 7c, f) correlations between $\Delta N_2 O$, AOU (Fig. 7c) and nitrate (Fig. 7f) were more pronounced. We observed different $\Delta N_2 O$ /AOU ratios at depths down to $\Delta N_2 O$ maxima and below the $\Delta N_2 O$ maxima down to the bottom. From the surface layer down to 500 m (σ_{θ} <27.1; see regression line a) the slope of the regression line ($\Delta N_2 O$ /AOU) was approximately 20 % lower than at depths below
- ²⁵ 500 m (σ_{θ} >27.1; see regression line b), what implies that the yield of N₂O at equal AOU is lower at shallower depths.

BGD 3, 993–1022, 2006						
Nitrous oxide in the North Atlantic Ocean S. Walter et al.						
Title Page						
Abstract Introduction						
Conclusions	References Figures					
Tables						
14	►I.					
•	F					
Back	Close					
Full Scre	en / Esc					
Printer-friendly Version						
Interactive Discussion						
EGU						

5 Discussion

25

Based on our results, we were able to assign measured N_2O concentrations to the water masses as shown in Fig. 2a (see Fig. 8). In the following we discuss distributions and possible origins of nitrous oxide at different depths with regard to these water masses.

5.1 N₂O in the surface layer of the North Atlantic

In the surface layer of the North Atlantic the distribution of N₂O was relatively uniform, with concentrations near equilibrium. This is in line with the assumption that denitrification and nitrification as sources of nitrous oxide in the surface layer seem to be negligible due to the high oxygen concentrations and light inhibition of nitrification (Horrigan et al., 1981). Thus, correlations between ΔN_2O , AOU and nitrate were nonexistent. Accordingly, we suggest that the N₂O distribution in the surface layer is most likely driven by solubility and mixing effects. This is also applicable for the enhanced N₂O concentrations found in the Labrador Current. The ΔN_2O concentrations, which are corrected for temperature, showed no enhanced values in this region. Thus, higher N₂O concentrations in the Labrador Current are likely caused by the solubility effect as well. In the warmer surface layer of the tropical North Atlantic ΔN_2O values were up to 4 nmol L⁻¹, indicating the tropical North Atlantic acts as a weak source for atmospheric N₂O (Walter et al., 2004).

20 5.2 N₂O below the surface layer down to 2000 m

Variations of N₂O vertical profiles reflected effects of water mass ventilation and subsurface N₂O production history. In the subpolar North Atlantic we assume that the hydrographic setting (such as convection processes during deep water formation and vertical mixing) is responsible for the observed concentrations and distributions of N₂O and Δ N₂O. The most important feature in the subpolar North Atlantic is the formation



of deep water in winter in the Labrador and Irminger Seas as part of the North Atlantic circulation in 500 to 2000 m (Rhein, 2000), which carries the atmospheric N₂O imprint to depth. Labrador Sea Water spreads rapidly east- and southwards (Rhein, 2000) and thus causes the uniform distribution of N₂O within the subpolar North Atlantic. Al-

- ⁵ though the productivity of phytoplankton is relatively high in the subpolar North Atlantic, we assume low biological production of N₂O because of two factors: 1) high oxygen concentrations and 2) low temperatures. The yield of N₂O depends on oxygen concentration (Goreau et al., 1980; Poth and Focht, 1985; Richardson, 2000; Codispoti et al., 1992), whereas high oxygen concentrations weaken the production of N₂O. Further-
- ¹⁰ more the low temperatures of the North Atlantic might have been crucial as well. The temperature dependence of both nitrification rates and enzyme activities is controversially discussed (Berounsky and Nixon, 1990; Vouve et al., 2000; Barnard et al., 2005; Herbert, 1999; Rheinheimer, 1964; Hansen et al., 1981; Rysgaard et al., 1996), however growth rates and biological production of bacteria clearly depend on the prevailing
 temperatures (Bock and Wagner, 2001; Hoppe et al., 2002). Thus, N₂O production might not be limited directly by temperature but indirectly by the limited abundance of N₂O producing bacteria.

In the subtropical North Atlantic concentrations of N₂O and ΔN₂O were distinctly higher compared to the subpolar North Atlantic. Profiles differed clearly between the western and eastern basin. N₂O profiles in the western basin showed clearly expressed N₂O maxima between 600 to 1000 m. This pattern was not observable east of the Midatlantic Ridge where N₂O and ΔN₂O concentrations were lower than in the western basin, and no peak maxima were observed. Hydrographic processes likely explain the shape of profiles, especially the advection of Labrador Sea Water (LSW)
 into the eastern basin. LSW with low N₂O concentrations is transported either along the eastern continental slope of America or across the Charlie-Gibbs-Fracture-Zone (Bower et al., 2002). It flows into the eastern subtropical basin at 500–2000 m (Rhein, 2000; Alvarez et al., 2004), and spreads north- and southwards (Bower et al., 2002; Rhein, 2000). In the western basin N₂O concentrations and profiles are in agree-



ment with profiles published by Yoshinari (1976), who also found maximum values in water masses with lower oxygen concentrations. These were identified as Antarctic Intermediate Water (AAIW), which flows northwards. We assume the AAIW transports N₂O from the south to the subpolar North Atlantic. At depths shallower than 1000 m (σ_{θ} <27.7) Δ N₂O was significantly correlated with oxygen utilization and nitrate concentrations (Figs. 7b, e; Table 1), indicating nitrification has contributed to measured N₂O concentrations.

In the tropical North Atlantic the N₂O profiles and the observed trend along the West-East transect are in overall agreement with recently published data from a transect along 7.5° N (Oudot et al., 2002) and a previous study in the Guinea Dome area (Oudot et al., 1990). Although the overall pattern is the same, we observed generally lower N₂O concentrations than Oudot et al. (2002). This might be a result of a calibration disagreement, supported by measured atmospheric N₂O values of 316 ppb in 1993. For example, we found a peak N₂O concentration of up to 37.3 nmol L⁻¹ in South Atlantic ¹⁵ Central Water (SACW) of the eastern basin, whereas Oudot et al. (2002) reported values of up to 60 nmol kg⁻¹. Oudot et al. (2002) assumed enhanced biological activity and remineralization of organic matter in upwelling ecosystems to be responsible for these higher values in the east. However, upwelling in this area is a temporary event (Voituriez et al., 1982; Siedler et al., 1992), and during our cruise no upwelling was

²⁰ observed.

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Despite the fact that upwelling might have a long-term large-scale effect, we suppose additional reasons for the higher N₂O concentrations in the eastern basin. The productivity in the eastern basin is fueled not only by coastal upwelling (Signorini et al., 1999) but also by dust deposition off the West African coast (Mills et al., 2004). ²⁵ Moreover, nutrient input by major tropical rivers such as the Senegal, Gambia and Niger (Perry et al., 1996) contribute to enhanced production off the West African coast, indicated by enhanced chlorophyll a concentrations (for the 2002 seasonal cycle of chlorophyll a see monthly data set of Sea-viewing Wide Field-of-view Sensor (Sea-WiFS: http://earthobservatory.nasa.gov/Observatory/Datasets/chlor.seawifs.html).



Enhanced productivity leads to a high export production (Antia et al., 2001). Subsequently lowered O_2 concentrations in the eastern intermediate layers due to the demineralization of organic matter support the production of N₂O. Therefore, enhanced N₂O concentrations in the eastern basin at this time of year (October/November 2002) might be a residual signal of past high production episode (Signorini et al., 1999).

Upwelling events, indicated by lower sea surface temperatures, were only found at the equator. Surface N_2O concentration and sea surface temperature were positively correlated (Walter et al., 2004), and the comparably shallow N_2O maxima along the equator were caused by upwelling.

- ¹⁰ Due to the occurrence of linear relationships between ΔN_2O and AOU and between N_2O and nitrate we conclude that nitrification might be the major pathway of N_2O formation in the tropical Atlantic Ocean (Yoshida et al., 1989). Like N_2O , ΔN_2O showed an increasing trend from West to East indicating that nitrification is more pronounced in the eastern than the western basin of the tropical Atlantic.
- 15 5.3 N₂ O in deep waters >2000 m (σ_{θ} >27.8)

Because the deep ocean contains high nitrate concentrations, nitrification was assumed to be responsible for N₂O production (Zehr and Ward, 2002; Bange and Andreae, 1999). Due to the low ΔN₂O in deep waters and insufficient correlations with nitrate and AOU, we assume N₂O at these depths probably originates from deep water formation and mixing processes of southern and northern hemisphere water masses. N₂O profiles from a cruise into the Antarctic circumpolar current (2° E/49.5° S) (Walter et al., 2005) and BLAST II data east of Patagonia reveal distinctly higher N₂O concentrations in the deep waters of the southern hemisphere, with values of approximately 17 nmol L⁻¹. Northwards transport within Antarctic Bottom Water could lead to enhanced N₂O concentrations in the deep water of the North Atlantic by mixing and diffusion process.

BGD						
3, 993–10	3, 993–1022, 2006					
Nitrous oxide in the North Atlantic Ocean						
S. Walter et al.						
Title Page						
Abstract	Introduction					
Conclusions	References					
Tables	Figures					
14	►I.					
•	•					
Back	Close					
Full Scre	Full Screen / Esc					
Printer-frier	Printer-friendly Version					
Interactive Discussion						
EGU						

6 Conclusions

15

N₂O concentrations in the North Atlantic showed characteristic variations in the vertical and horizontal distributions. In general, distribution of N₂O can be explained by a combination of biological and hydrographic reasons. The main conclusions of the present study are

- Production of N₂O by nitrification occurs mainly in the tropical North Atlantic, especially in the eastern basin. Maximum values were found in the Antarctic Intermediate Water (AAIW) in the western basin, and in the South Atlantic Central Water (SACW) in the eastern basin.
- Vertical N₂O distribution and shape of profiles in the subtropical North Atlantic originate from production by nitrification and advection of AAIW from the south into the western subtropical North Atlantic, respectively advection of LSW from the north in the eastern subtropical North Atlantic.
 - In the subpolar North Atlantic mainly mixing processes may control the distribution of N₂O, particularly the deep water formation in the Labrador Sea. Production seems to be negligible.
 - Tropical and subtropical regions showed supersaturation throughout the water column, thus the tropical and subtropical North Atlantic act as a source of atmospheric N₂O.
- Outflow water of the Amazon or the Mediterranean Sea does not affect the N₂O concentration.

Acknowledgements. We thank the captains and crews of FS Meteor and FS Gauss for their help during sampling. We especially thank P. Fritsche, H. P. Hansen, F. Malien and J. Schafstall for nutrient and oxygen measurements and CTD handling during the Meteor cruises. Thanks to

²⁵ K. P. Koltermann and his colleagues of the Bundesamt für Seeschifffahrt und Hydrographie in Hamburg for the opportunity to participate on the cruise "Gauss 384-1". Thanks to R. Hoffmann

BGD						
3, 993–10	3, 993–1022, 2006					
Nitrous oxide in the North Atlantic Ocean						
S. Walter et al.						
litle	Title Page					
Abstract	Introduction					
Conclusions	References					
Tables	Figures					
14	►I					
•	•					
Back	Close					
Full Screen / Esc						
Printer-frier	Printer-friendly Version					
Interactive Discussion						
EGU						

(Max Planck Institute for Chemistry, Mainz, Germany) for calibration of our standard gas mixtures. This study was financially supported by the Deutsche Forschungsgemeinschaft (DFG) by grants no WA1434/1, WA1434/3, and WA 1434/5.

References

20

- Aiken, J., Rees, N., Hooker, S., Holligan, P., Bale, A., Robins, D., Moore, G., Harris, R., and Pilgrim, D.: The Atlantic Meridional Transect: overview and synthesis of data, Prog. Oceanogr., 45(3–4), 257–312, 2000.
 - Alvarez, M., Perez, F. F., Bryden, H., and Rios, A. F.: Physical and biogeochemical transports structure in the North Atlantic subpolar gyre, J. Geophys. Res.-Oceans, 109(C3), 2004.
- Antia, A. N., Koeve, W., Fischer, G., Blanz, T., Schulz-Bull, D., Scholten, J., Neuer, S., Kremling, K., Kuss, J., Peinert, R., Hebbeln, D., Bathmann, U., Conte, M., Fehner, U., and Zeitzschel, B.: Basin-wide particulate carbon flux in the Atlantic Ocean: Regional export patterns and potential for atmospheric CO₂ sequestration, Global Biogeochem. Cycles, 15(4), 845–862, 2001.
- ¹⁵ Bange, H. W. and Andreae, M. O.: Nitrous oxide in the deep waters of the world's oceans, Global Biogeochem. Cycles, 13(4), 1127–1135, 1999.

Bange, H. W., Rapsomanikis, S., and Andreae, M. O.: Nitrous oxide cycling in the Arabian Sea, J. Geophys. Res.-Oceans, 106(C1), 1053–1065, 2001.

Barnard, R., Leadley, P. W., and Hungate, B. A.: Global change, nitrification, and denitrification: A review, Global Biogeochem. Cycles, 19(1), doi:10.1029/2004GB002282, 2005.

- Berounsky, V.M. and Nixon, S.W.: Temperature and the annual cycle of nitrification in waters of Narragansett Bay, Limnol. Oceanogr., 35(7), 1610–1617, 1990.
 - Bock, E. and Wagner, M.: Oxidation of inorganic nitrogen compounds as an energy source, in: The Prokaryotes: An Evolving Electronic Resource for the Microbiological Community,
- ²⁵ 3rd edition, release 3.7, Springer Verlag, New York, http://141.150.157.117:8080/prokPUB/ index.htm, 2001.
 - Bower, A. S., Le Cann, B., Rossby, T., Zenk, W., Gould, J., Speer, K., Richardson, P. L., Prater, M. D., and Zhang, H. M.: Directly measured mid-depth circulation in the northeastern North Atlantic Ocean, Nature, 419(6907), 603–607, 2002.

BGD 3, 993–10∠2, 2006 Nitrous oxide in the North Atlantic Ocean S. Walter et al. Title Page Abstract Introduction Conclusions References Tables Figures

Back

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Close

- Broecker, W. S. and Peng, T.-H.: Comparison of ³⁹Ar and ¹⁴C ages for waters in the deep ocean, Nucl. Instrum. Meth. B, 172, 473–478, 2000.
- Butler, J. H., Lobert, J. M., Yvon, S. A., and Geller, L. S.: The distribution and cycling of halogenated trace gases, in: Reports on Polar Research No. 168 – The expedition ANTARKTIS
- 5 XII of RV "Polarstern" in 1994/95: Reports of legs ANT XII/1 and 2, edited by: Kattner, G. and Fütterer, D. K., 33–40, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, 1995.
 - Codispoti, L. A., Brandes, J. A., Christensen, J. P., Devol, A. H., Naqvi, S. W. A., Paerl, H. W., and Yoshinari, T.: The oceanic fixed nitrogen and nitrous oxide budgets: Moving targets as we enter the anthropocene?, Sci. Mar., 65(Suppl. 2), 85–105, 2001.
- Codispoti, L. A., Elkins, J. W., Yoshinari, T., Friederich, G. E., Sakamoto, C. M., and Packard, T. T.: On the nitrous oxide flux from productive regions that contain low oxygen waters, 271–284, Oxford and IBH, New Delhi (India), 1992.

10

30

Cohen, Y. and Gordon, L. I.: Nitrous oxide in the oxygen minimum of the eastern tropical North

- Pacific: evidence for its consumption during denitrification and possible mechanisms for its production, Deep-Sea Res., 25(6), 509–524, 1978.
 - Flückiger, J., Dallenbach, A., Blunier, T., Stauffer, B., Stocker, T. F., Raynaud, D., and Barnola, J. M.: Variations in atmospheric N₂O concentration during abrupt climatic changes, Sci., 285(5425), 227–230, 1999.
- Fratantoni, D. M. and Glickson, D. A.: North Brazil current ring generation and evolution observed with SeaWiFS, J. Phys. Oceanogr., 32(3), 1058–1074, 2002.
 - Gordon, A. L.: Interocean exchange of thermohaline water, J. Geophys. Res., 91, 5037–5047, 1986.

Goreau, T. J., Kaplan, W. A., Wofsy, S. C., McElroy, M. B., Valois, F. W., and Watson, S. W.:

- Production of NO₂⁻ and N₂O by nitrifying bacteria at reduced concentrations of oxygen, Appl. Environ. Microbiol., 40(3), 526–532, 1980.
 - Hansen, J. I., Blackburn, T. H., and Henriksen, K.: Seasonal distribution of nitrifying bacteria and rates of nitrification in coastal marine sediments, Microb. Ecol., 7(4), 297–304, 1981.
 Herbert, R. A.: Nitrogen cycling in coastal marine ecosystems, FEMS Microbiol. Rev., 23, 563– 590, 1999.
 - Hoppe, H. G., Gocke, K., Koppe, R., and Begler, C.: Bacterial growth and primary production along a north-south transect of the Atlantic Ocean, Nature, 416(6877), 168–171, 2002.
 Horrigan, S. G., Carlucci, A. F., and Williams, P. M.: Light inhibition of nitrification in sea-surface

BGD					
3, 993–1022, 2006					
Nitrous oxide in the North Atlantic Ocean S. Walter et al.					
Title	Page				
Abstract	Introduction				
Conclusions	References				
Tables	Figures				
14	►I.				
	•				
Back Close					
Full Screen / Esc					
Printer-friendly Version					
Interactive Discussion					
EGU					

films, J. Mar. Res., 39(3), 557-565, 1981.

20

25

- Joyce, T. M., Hernandez-Guerra, A., and Smethie, W. M.: Zonal circulation in the NW Atlantic and Caribbean from a meridional World Ocean Circulation Experiment hydrographic section at 66° W, J. Geophys. Res.-Oceans, 106(C10), 22095–22113, 2001.
- ⁵ Junge, C. and Hahn, J.: N₂O measurements in the North Atlantic, J. Geophys. Res., 76(33), 8143–8146, 1971.
 - Körtzinger, A.: A significant CO₂ sink in the tropical Atlantic Ocean associated with the Amazon River plume, Geophys. Res. Lett., 30(24), 2287, doi:10.1029/2003GL018841, 2003.
 - Krauss, W.: Comments on the development of our knowledge of the general circulation of the
- North Atlantic Ocean, in: The Warmwatersphere of the North Atlantic Ocean, edited by: Krauss, W., 1–31, Gebrüder Borntraeger, Berlin-Stuttgart, 1996.
 - Lorbacher, K.: Niederfrequente Variabilität meridionaler Transporte in der Divergenzzone des nordatlantischen Subtropen- und Subpolarwirbels Der WOCE-Schnitt A2, Bericht des Bundesamtes für Seeschiftfahrt und Hydrographie, 22, 156, 2000.
- ¹⁵ Mills, M. M., Ridame, C., Davey, M., La Roche, J., and Geider, R. J.: Iron and phosphorus co-limit nitrogen fixation in the eastern North Atlantic, Nature, 429, 292–294, 2004.
 - Najjar, R. G.: Marine biogeochemistry, in: Climate System Modeling, edited by: Trenberth, K. E., 241–280, Cambridge University Press, Cambridge, 1992.

Oudot, C., Andrie, C., and Montel, Y.: Nitrous oxide production in the tropical Atlantic Ocean, Deep-Sea Res. I, 37(2), 183–202, 1990.

- Oudot, C., Jean-Baptiste, P., Fourre, E., Mormiche, C., Guevel, M., Ternon, J.-F., and Le Corre, P.: Transatlantic equatorial distribution of nitrous oxide and methane, Deep-Sea Res. I, 49, 1175–1193, 2002.
- Perry, G.D., Duffy, P.B., and Miller, N.L.: An extended data set of river discharges for validation of general circulation models, J. Geophys. Res., 101(D16), 21 339–21 349, 1996.
- Poole, R. and Tomczak, M.: Optimum multiparameter analysis of the water mass structure in the Atlantic Ocean thermocline, Deep-Sea Res. I-Oceanographic Research Papers, 46(11), 1895–1921, 1999.

Popp, B. N., Westley, M. B., Toyoda, S., Miwa, T., Dore, J. E., Yoshida, N., Rust, T. M., Sansone,

F. J., Russ, M. E., Ostrom, N. E., and Ostrom, P. H.: Nitrogen and oxygen isotopomeric constraints on the origins and sea-to-air flux of N₂O in the oligotrophic subtropical North Pacific gyre, Global Biogeochem. Cycles, 16(4), 1064, doi:10.1029/2001GB001806, 2002.
 Poth, M. and Focht, D. D.: ¹⁵N kinetic analysis of N₂O production by *Nitrosomonas europaea* -

BGD

3, 993–1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.



an examination of nitrifier denitrification, Appl. Environ. Microbiol., 49(5), 1134–1141, 1985. Prather, M., Ehhalt, D., Dentener, F., Derwent, R., Dlugokencky, E., Holland, E., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P., Midgley, P., and Wang, M.: Atmospheric chemistry and greenhouse gases, in: Climate Change 2001: The Scientific Basis. Contribution of Working

Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., Van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., 239–287, Cambridge University Press, Cambridge, UK, 2001.

Rhein, M.: Oceanography – Drifters reveal deep circulation, Nature, 407(6800), 30–31, 2000.

¹⁰ Rheinheimer, G.: Untersuchungen über den Einfluß der Temperatur auf die Nitrifikation im Elbe-Aestuar, Arch. Mikrobiol., 49, 283–290, 1964.

Richardson, D. J.: Bacterial respiration: a flexible process for a changing environment, Microbiol., 146, 551–571, 2000.

Richardson, P. L., Bower, A. S., and Zenk, W.: A census of Meddies tracked by floats, Prog. Oceanogr., 45(2), 209–250, 2000.

Robertson, L. A., van Niel, E. W. J., Torremans, R. A. M., and Kuenen, J. G.: Simultaneous nitrification and denitrification in aerobic chemostat cultures of *Thiosphaera pantotropha*, Appl. Environ. Microbiol., 54(11), 2812–2818, 1988.

Rysgaard, S., Finster, K., and Dahlgaard, H.: Primary production, nutrient dynamics and min-

- eralisation in a northeastern Greenland fjord during the summer thaw, Polar Biol., 16(7), 497–506, 1996.
 - Seitzinger, S. P., Kroeze, C., and Styles, R. V.: Global distribution of N₂O emissions from aquatic systems: Natural emissions and anthropogenic effects, Chemosphere: Global Change Sci., 2(3), 267–279, 2000.
- Siedler, G., Zangenberg, N., and Onken, R.: Seasonal changes in the tropical Atlantic circulation - Observation and simulation of the Guinea Dome, J. Geophys. Res.-Oceans, 97(C1), 703–715, 1992.

Signorini, S. R., Murtugudde, R. G., McClain, C. R., Christian, J. R., Picaut, J., and Busalacchi, A. J.: Biological and physical signatures in the tropical and subtropical Atlantic, J. Geophys.

³⁰ Res.-Oceans, 104(C8), 18367–18382, 1999.

15

Snowden, D. P. and Molinari, R. L.: Subtropical cells in the Atlantic Ocean: An observational summary, in: Interhemispheric Water Exchange in the Atlantic Ocean, edited by: Goni, G. J. and Malanotte-Rizzoli, P., 287–312, Elsevier, New York, 2003.

B(3, 993–1	GD 022, 2006			
Nitrous of North Atla	xide in the ntic Ocean			
S. Walt	ter et al.			
Title	Page			
Abstract	Introduction			
Conclusions	References			
Tables	Figures			
14	►I.			
•	F			
Back	Close			
Full Scr	een / Esc			
Printer-frie	ndly Version			
Interactive	Discussion			
F	311			

- Tomczak, M.: Some historical, theoretical and applied aspects of qualitative water mass analysis, J. Mar. Res., 57, 275–303, 1999.
- Tomczak, M. and Godfrey, J. S.: Regional Oceanography: An Introduction, http://www.es. flinders.edu.au/~mattom/regoc/pdfversion.html, 2001.
- 5 Voituriez, B., Herbland, A., and Leborgne, R.: Equatorial upwelling in the eastern Atlantic during FGGE, Oceanol. Acta, 5(3), 301–314, 1982.
 - Vouve, F., Guiraud, G., Marol, C., Girard, M., Richard, P., and Laima, M. J. C.: NH₄⁺ turnover in intertidal sediments of Marennes-Oleron Bay (France): effect of sediment temperature, Oceanol. Acta, 23(5), 575–584, 2000.
- ¹⁰ Wallace, D. W. R. and Bange, H. W.: Introduction to special section: Results of the Meteor 55: Tropical SOLAS Expedition, Geophys. Res. Lett., 31, L23S01, 1–4, 2004.
 - Walter, S., Bange, H. W., and Wallace, D. W. R.: Nitrous oxide in the surface layer of the tropical North Atlantic Ocean along a west to east transect, Geophys. Res. Lett., 31(23), L23S07, doi:10.1029/2004GL019937, 2004.
- ¹⁵ Walter, S., Peeken, I., Lochte, K., and Bange, H. W.: Nitrous oxide measurements during EIFEX, the European Iron Fertilisation Experiment in the subpolar South Atlantic Ocean, Geophys. Res. Lett., 32, L23613, doi:10.1029/2005GL024619, 2005.
 - Weiss, R. F.: The solubility of nitrogen, oxygen and argon in water and seawater, Deep-Sea Res., 17, 721–735, 1970.
- ²⁰ Weiss, R. F. and Price, B. A.: Nitrous oxide solubility in water and seawater, Mar. Chem., 8, 347–359, 1980.
 - Yoshida, N., Morimoto, H., Hirano, M., Koike, I., Matsuo, S., Wada, E., Saino, T., and Hattori, A.: Nitrification rates and ¹⁵N abundances of N₂O and NO₃⁻ in the western North Pacific, Nature, 342, 895–897, 1989.
- ²⁵ Yoshinari, T.: Nitrous oxide in the sea, Mar. Chem., 4, 189–202, 1976.
- Yoshinari, T., Altabet, M. A., Naqvi, S. W. A., Codispoti, L., Jayakumar, A., Kuhland, M., and Devol, A.: Nitrogen and oxygen isotopic composition of N₂O from suboxic waters of the eastern tropical North Pacific and the Arabian Sea - Measurement by continuous-flow isotope-ratio monitoring, Mar. Chem., 56(3–4), 253–264, 1997.
- ³⁰ Zehr, J. P. and Ward, B. B.: Nitrogen cycling in the ocean: New perspectives on processes and paradigms, Appl. Environ. Microbiol., 68(3), 1015–1024, 2002.

3, 993–1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.



3, 993–1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.

Title Page					
Abstract	Introduction				
Conclusions	References				
Tables	Figures				
I.	►I.				
•	•				
Back	Close				
Full Screen / Esc					
Printer-friendly Version					
Interactive Discussion					
FGU					

Table 1. Regression analyses between ΔN_2O and AOU, and ΔN_2O and NO_3^- at different isopycnal levels. Bold numbers mean relationships with significance levels of p<0.001 and R²>0.5. The coefficients a and b mean slope and intercept.

				ΔN ₂ O/AOU			$\Delta N_2 O/NO_3^-$			
	region	sigma	n	а	b	R^2	a	b	R^2	
	subpolar	thermocline-26.0	_	_	_	_	-	_	_	
		26.1-26.5	_	_	_	_	_	_	_	
		26.6-27.0	13	0.045	-0.209	0.21	0.205	-0.882	0.09	
		27.1–27.5	49	0.028	-0.452	0.23	0.159	-1.087	0.14	
		27.6–27.9	179	0.022	-1.714	0.07	0.164	-3.240	0.03	
	subtropical	thermocline-26.0	_	_	_	_	_	_	_	
		26.1-26.5	45	0.038	1.307	0.58	0.297	1.337	0.51	
		26.6-27.0	106	0.065	0.397	0.75	0.390	0.186	0.68	
		27.1–27.5	121	0.055	0.426	0.67	0.312	-0.052	0.60	
		27.6–27.9	355	0.069	-3.083	0.38	-0.126	4.579	0.02	
	tropical	thermocline-26.0	34	0.080	3.783	0.72	0.599	4.681	0.61	
		26.1-26.5	39	0.099	-1.421	0.83	0.777	-3.212	0.81	
		26.6-27.0	98	0.107	-3.112	0.49	0.376	6.068	0.20	
		27.1–27.5	63	0.114	-10.638	0.43	1.289	-35.05	0.42	
		27.6–27.9	69	0.075	-4.853	0.67	0.619	-11.83	0.66	



BGD

3, 993–1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.



Fig. 1. Cruise tracks for "Gauss 384-1" (subpolar North Atlantic, 16 May to 14 June 2002), "Meteor 60-5" (subtropical North Atlantic, 9 March to 14 April 2004) and "Meteor 55" (tropical North Atlantic, 13 October to 16 November 2002). Numbers are given for stations where N_2O profiles were measured.



Fig. 2. T-S-diagram of the North Atlantic; **(a)** T-S-diagram with data from all three cruises; **(b)** T-S-diagram in (a) framed by box.; AW: Amazon Water; STMW: Subtropical Mode Water; MW: Mediterranean Water; SACW: South Atlantic Central Water; NACW: North Atlantic Central Water; AAIW: Antarctic Intermediate Water, AABW: Antarctic Bottom Water; INADW: lower North Atlantic Deep Water; uNADW: upper North Atlantic Deep Water; LSW: Labrador Sea Water.

3, 993–1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.





Fig. 3. Distribution of N₂O in the North Atlantic along isopycnal levels σ_{θ} [kg m⁻³]. Dots indicate stations with available data for the isopycnal levels. (a) surface-thermocline; (b) thermocline-26.0; (c) 26.1–26.5; (d) 26.6–27.0; (e) 27.1–27.5; (f) 27.6–27.93.



EGU

3, 993–1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.







3, 993–1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.







3, 993–1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.





Fig. 6. $\Delta N_2 O$ in comparison with AOU (a) and nitrate (b) for the North Atlantic, sigma σ_{θ} is colour coded in kg m⁻³. $y(\Delta N_2 O)=0.089x(AOU)-3.245$, R²=0.714 $y(\Delta N_2 O)=0.331x(NO_3^-)-1.263$, R²=0.322.





3, 993-1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.



Fig. 7. $\Delta N_2 O$ in comparison with AOU (**a**–**c**) and nitrate (**d**–**f**), sigma σ_{θ} is colour coded in kg m⁻³.

(a) and (d) subpolar North Atlantic

(b) and (e) subtropical North Atlantic;

y ($\Delta N_2 O$)=0.0473x(AOU)+1.1409, R²=0.86 for $\sigma_{\theta} < 27.7 (\sim <1000 \text{ m});$

y (ΔN_2O)=0.2497x(NO_3^-)+1.1776, R²=0.80 for σ_{θ} < 27.7(~ <1000 m);

circled data represent σ_{θ} > 27.7(~>1000 m)

(c) and (f) tropical North Atlantic;

line a: y ($\Delta N_2 O$)=0.0785x(AOU)+2.4381, R²=0.87 for σ_{θ} < 27.1(~<500 m); line b: y ($\Delta N_2 O$)=0.0942x(AOU)-6.6675, R²=0.81 for σ_{θ} > 27.1(~>500 m); line a: y ($\Delta N_2 O$)=-0.4848x(NO₃⁻)+3.1756, R²=0.79 for σ < 27.1(~<500 m); line b: y ($\Delta N_2 O$)=0.7379x(NO₃⁻)-14.665, R²=0.79 for σ > 27.1 (~>500 m).

3, 993–1022, 2006

Nitrous oxide in the North Atlantic Ocean

S. Walter et al.





Fig. 8. N₂O concentration (a) and Δ N₂O (b) distributed in a T-S-diagram, the N₂O and Δ N₂O concentrations are colour coded in nmol L⁻¹. AW: Amazon Water; STMW: Subtropical Mode Water; MW: Mediterranean Water; SACW: South Atlantic Central Water; NACW: North Atlantic Central Water; AAIW: Antarctic Intermediate Water; LSW: Labrador Sea Water.