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Nitrous oxide emissions from the upwelling area off Mauritania (NW Africa)

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[1] Nitrous oxide (N_2O) flux densities across the ocean/atmosphere interface from the Mauritanian upwelling (16°–18.5°W, 16°–21°N) were computed with a simple upwelling model using N_2O measurements from four cruises between 2006 and 2008 as well as wind data from the QuikSCAT satellite. The resulting N_2O flux densities show a strong seasonality reflecting the wind-driven seasonality of the upwelling: N_2O flux densities are highest in the northern part (19.5°–21°N) and show a decreasing trend towards the south. The summer periods with no upwelling (and thus associated with no or negligible N_2O flux densities) are most pronounced in the southern part (16°–17°N). The mean seasonally and regionally weighted annual N_2O emissions from the Mauritanian upwelling were estimated to 1.0 Gg N. This is low compared to other major upwelling areas (Arabian Sea, off Chile) indicating that N_2O emissions from the Mauritanian upwelling are a minor source of atmospheric N_2O. **Citation:** Wittke, F., A. Kock, and H. W. Bange (2010), Nitrous oxide emissions from the upwelling area off Mauritania (NW Africa), *Geophys. Res. Lett.*, *37*, L12601, doi:10.1029/2010GL042442.

1. Introduction

[2] Nitrous oxide (N_2O) is a gaseous trace component of the Earth's atmosphere and contributes significantly to both the greenhouse effect and the stratospheric ozone depletion [*Forster et al.*, 2007; *Ravishankara et al.*, 2009]. Main formation pathways of N_2O are microbial nitrification and denitrification leading to an accumulation of N_2O in oceanic subsurface layers [see, e.g., *Bange*, 2008]. The world's oceans, including their coastal zones, are a major source for N_2O and contribute about 30% to the global atmospheric N_2O budget [*Bange*, 2006; *Denman et al.*, 2007]. The major coastal upwelling areas such as found in the Arabian Sea and in the eastern tropical North and South Pacific are well-known as sites of enhanced N_2O emissions to the atmosphere [*Bange et al.*, 2001; *Cornejo et al.*, 2006; *Lueker et al.*, 2003]. Coastal upwelling areas may contribute about 1-5% to the overall oceanic N_2O emissions [*Bange et al.*, 1996a; *Nevison et al.*, 2004]. However, detailed studies of N_2O emissions from major upwelling areas such as off NW Africa (Morocco/Mauritania) are missing. Based on the 'wind-only' upwelling model approach by *Nevison et al.* [2004] and N_2O measurements from four cruises to the coastal area off Mauritania between 2006 and 2008, we present a first regionally and seasonally weighted estimate of N_2O emissions from the coastal upwelling off Mauritania (21°–16°N).

2. Study Site Description

[3] The eastern tropical North Atlantic Ocean is an area with strongly differing hydrographic and biological properties: On the one hand, the Canary and North Equatorial Currents form the eastern part of the North Atlantic Subtropical Gyre which is a zone of low nutrient-supply and thus low primary production. On the other hand nutrient-rich upwelled water masses feed zones of high biological productivity off the Northwest African coast. Upwelling events off Mauritania are characterized by a pronounced drop in sea surface temperatures (SST). SST of <17°C are typical for upwelled water masses along the coast [*Mittelstaedt*, 1986]. The coastal upwelling occurs within a narrow (10–20 km) band along the continental slope as a consequence of offshore Ekman transport due to the trade winds along the Mauritanian coastline. The upwelled water is coming from a water depth of about 100–200 m [*Hagen*, 2001; *Mittelstaedt*, 1986]. The occurrence of the upwelling shows a seasonality following the shifting of the Inter-Tropical Convergence Zone (ITCZ) throughout the year [*Hagen*, 2001]. In the region between Cap Vert (~15°N) and Cap Blanc (~21°N) seasonal upwelling takes place during winter/spring with the southernmost extension in February [*Nykjær and Van Camp*, 1994; *Schemainda et al.*, 1975; *Wooster et al.*, 1976].

3. Methods

[4] N_2O flux densities (F_{N2O}) across the ocean/atmosphere interface were calculated as

$$F_{N2O} = k_w(C_w - C_a), \quad (1)$$

where k_w is the gas exchange coefficient and C_w is the N_2O concentration in the ocean surface layer. C_a is the estimated N_2O equilibrium concentration and was calculated as

$$C_a = \beta x' P, \quad (2)$$

where β is the Bunsen solubility of N_2O in seawater [*Weiss and Price*, 1980]. β was calculated with monthly surface temperatures and salinities from the World Ocean Atlas 2005 [*Antonov et al.*, 2006; *Locarnini et al.*, 2006]. P is the ambient pressure (set to 1 atm) and x' is the dry mole fraction in the ambient air. For x' we used the monthly time series of atmospheric N_2O from the Advanced Global Atmospheric Gases Experiment (AGAGE) monitoring station Ragged

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Table 1. Concentrations of N_2O in 100 m (C_{100m}) From Four Cruises Between 2006 and 2008

Latitude (°N)	Longitude (°W)	Cruise	Date	$C_{100m} \pm 1$ SD[a] (nmol L^{-1})
18.0	17.0	M68/3	Jul 2006	22.7 ± 1.2
17.5	17.0	M68/3	Jul 2006	35.8 ± 0.3
18.0	16.5	M68/3	Jul 2006	35.7 ± 1.3
18.5	16.8	P347	Jan 2007	22.6 ± 2.5
17.5	16.5	P347	Jan 2007	31.7 ± 0.7
18.0	17.0	P348	Feb 2007	27.1 ± 0.6
19.0	17.0	P348	Feb 2007	32.5 ± 0.2
18.0	16.5	P348	Feb 2007	27.6 ± 0.1
20.0	18.0	ATA3	Feb 2008	28.0 ± 0.3
20.1	17.7	ATA3	Feb 2008	21.9 ± 0.8
16.2	17.1	ATA3	Feb 2008	28.3 ± 0.2
18.0	17.0	ATA3	Feb 2008	24.8 ± 0.7
17.0	17.0	ATA3	Feb 2008	31.2 ± 0.9
19.0	16.9	ATA3	Feb 2008	26.9 ± 0.4
17.0	16.8	ATA3	Feb 2008	33.5 ± 0.9
17.8	16.6	ATA3	Feb 2008	31.5 ± 0.9
17.8	16.6	ATA3	Feb 2008	30.8 ± 0.5

[a]SD stands for (estimated) standard deviation; for details of the calculation see *Walter et al.* [2006].

Point on Barbados (see http://agage.eas.gatech.edu) [*Prinn et al.*, 2000]. For the calculation of k_w we used the approach of *Nightingale et al.* [2000]:

$$k_w = 0.01/3600\left(0.222u^2 + 0.333u\right)\left(Sc_{N2O}/600\right)^{-n}, \quad (3)$$

where u is the wind speed in 10 m height, Sc_{N2O} is the Schmidt number of N_2O and n equals −0.66 for $0 < u < 3.6$ m s^{-1} or $n = -0.5$ for $u > 3.6$ m s^{-1}. Sc_{N2O} was calculated as the ratio of the kinematic viscosity of seawater and the diffusion of N_2O in water [see *Walter et al.*, 2004, and references therein]. C_w was calculated following the 'wind-only' upwelling model approach described by *Nevison et al.* [2004]:

$$C_w = C_{100m} Q_w Q_t, \quad (4)$$

where C_{100m} is the N_2O concentration in 100 m water depth which is assumed to be brought to the surface by upwelling. Q_w and Q_t are scaling functions depending on the upwelling velocity and time history of the upwelling (for details and parameters used see *Nevison et al.* [2004]). C_{100m} was taken from N_2O profiles measured during four cruises between 2006 and 2008 (Table 1) conducted by the SOPRAN (Surface Ocean Processes in the Anthropocene: www.sopran.pangaea.de) project which is a German contribution to international SOLAS (Surface Ocean – Lower Atmosphere Study: www.solas-int.org). N_2O was measured according to the method described in *Walter et al.* [2006]. The data presented in Table 1 are in agreement with C_{100m} (32.4 and 29.0 nmol L^{-1}) at two stations (20.6°N, 18.2°W and 20.3°N, 17.8°W, respectively) measured off Mauritania in September 2003 [*Forster et al.*, 2009].

[5] Wind data were derived from an active microwave sensor (SeaWinds scatterometer) onboard of the National Aeronautics and Space Administration (NASA) QuikSCAT satellite (http://podaac.jpl.nasa.gov), which measures near-surface values of the scalar wind speed and the meridional and zonal components of wind velocity and direction under all weather and cloud conditions over the ice-free ocean [*Liu*, 2002]. The QuikSCAT wind data used in our study have a spatial resolution of 25 km × 25 km and provide one measurement for the grid cells per day. A comparison of monthly mean QuikSCAT winds for 2001 with measured wind data from buoys deployed worldwide revealed a good correlation ($r = 0.92$), a root-mean-square difference of 0.7 m s^{-1} and a standard deviation for the QuikSCAT winds of ±1.7 m s^{-1} [*Wallcraft et al.*, 2009]. Rain events and the existence of gaps decrease the accuracy of the data [*Liu*, 2002; *Wallcraft et al.*, 2009], however, this constraint is negligible for the area discussed here. For further calculations the v (i.e., the N–S) component of the wind speed, which is driving the Ekman upwelling, was used.

[6] Following *Nevison et al.* [2004] we assumed that upwelling takes place when the winds were blowing for more than three days with a wind speed $u_{crit} > 4.6$ m s^{-1}. u_{crit} was determined as

$$u_{crit} = \left(\omega_{crit}\, \rho_w\, f\, R_b/(\rho_a\, C_d)\right)^{0.5}, \quad (5)$$

where ω_{crit} is the velocity threshold for the onset of upwelling (10^{-5} m s^{-1}), ρ_w and ρ_a are the densities of seawater (1025 kg m^{-3}) and atmosphere (1.3 kg m^{-3}), respectively; f is the Coriolis force (4.55 s^{-1}), R_b is the Rossby radius of deformation (35.2 km) [*Emery et al.*, 1984] and C_d is the dimensionless drag coefficient (0.0012). ω_{crit}, ρ_w and ρ_a were adapted from *Nevison et al.* [2004].

[7] In order to estimate the annual N_2O emissions from the upwelling off Mauritania, we divided the upwelling region into 10 boxes with a latitudinal spacing of 0.5° (Figure 1). For each of the given QuikSCAT coordinates within each latitudinal box, F_{N2O} was calculated for the calendar years 2006–2008 as described above. On the basis of the data in Table 1 we computed mean annual C_{100m} of 31 ± 7 nmol L^{-1} (2006), 28 ± 4 nmol L^{-1} (2007) and 29 ± 4 nmol L^{-1} (2008). Please note that potential seasonal and spatial variabilities of C_{100m} as implied by the variability of the concentrations which range from 21.9 ± 0.8 to 35.8 ± 0.3 nmol L^{-1} (see Table 1) are not accounted for in our approach. This introduces an uncertainty in our computa-

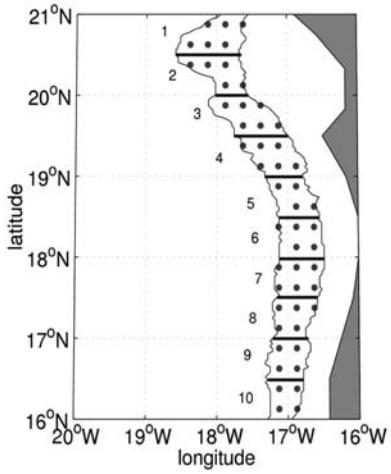

Figure 1. Schematic representation of the coastal region off Mauritania. The points represent the coordinates of available QuikSCAT data within the boxes #1–#10 (see text for details.)

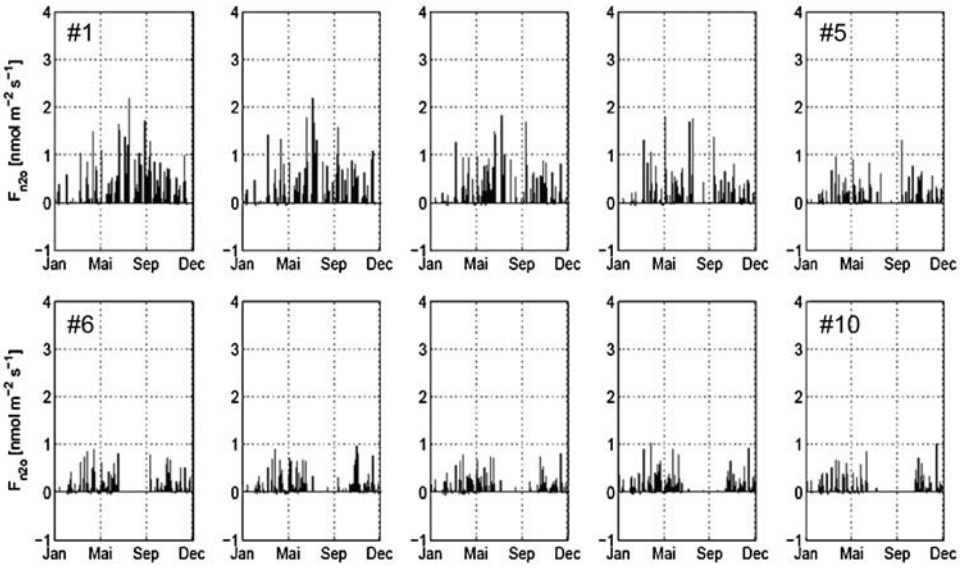

Figure 2. Time series of N_2O flux densities for the boxes #1–#10 (see Figure 1). Periods without data originate from times when $u_{crit} < 4.6$ m s^{-1} and indicate periods of no upwelling.

tions which cannot be quantified reasonably because of the rather poor temporal and spatial data coverage of the Mauritania upwelling area. The mean annual F_{N2O} for each box was then calculated as the average of the individual annual F_{N2O} within the box. Multiplying the mean annual flux densities with the area of the box yielded the mean annual N_2O emissions for each box which were then added to yield the overall mean annual N_2O emissions for the years 2006–2008.

4. Results and Discussion

[8] Figure 2 shows the time series of N_2O flux densities for the boxes #1–#10 for the year 2008. (The time series for 2006 and 2007 are very similar to the one from 2008 and are, therefore, not shown.) Two trends are visible: 1) The data from boxes #1–#3 (21°–19.5°N) show flux densities throughout the year, whereas the data from boxes #4–10 (19.5°–16.0°N) show periods during the summer where no flux densities were computed because the upwelling criterion was not matched (cf. equation (5)). The period with no upwelling reaches its maximum duration (July to October) in the southern most box (16.5°–16.0°N). 2) In general the flux densities are higher in the northern boxes (maximum > 2 nmol m^{-2} s^{-1}) and decrease considerably towards the south (maximum < 1 nmol m^{-2} s^{-1}). The N_2O flux densities are obviously driven by the magnitude and seasonality of the wind speeds and, thus, reflect the seasonality of the upwelling off Mauritania (see study site description). However, the simple approach applied here does not take into account potential stratification of the water column and currents. Both effects are known to reduce the effective Ekman upwelling and, therefore, the N_2O flux densities presented in Figure 2 are most likely overestimated. Calculations with a 3D high resolution model for the Atlantic Ocean (FLAME, Family of Linked Atlantic Model Experiments; http://www.ifmgeomar.de/index.php?id=3239&L=1) [*Glessmer et al.*, 2009] revealed that the vertical upwelling velocities of the *Nevison et al.*'s [2004] approach are well correlated with the seasonality of the vertical velocity in 100 m, however, they were in general about 1.5 times higher. A correction factor of 0.68 was calculated based on the mean difference of the Ekman upwelling and the vertical velocity in 100 m averaged for the area 16°–18.5°W, 16°–21°N [*Wittke*, 2009]. The correction factor was applied to adjust the N_2O flux densities: The uncorrected and corrected N_2O emissions for the individual calendar years range from 0.9 to 1.1 Gg N yr^{-1} and 0.5 to 0.7 Gg N yr^{-1}, respectively. The mean total N_2O emissions from the Mauritanian upwelling for 2006–2008 are 1.0 Gg N yr^{-1} (corrected: 0.6 Gg N yr^{-1}). Because the estimated error of the N_2O emission for the individual calendar years is about ±2 Gg N yr^{-1} [*Wittke*, 2009] it is impossible to detect any interannual variability or long-term trend.

[9] For comparison, *Nevison et al.*'s [2004] estimate for the upwelling off NW Africa (2.4 * 10^5 km^2 between 5°–30°N) is 22 Gg N yr^{-1}. Downscaling their estimate to the upwelling area considered in our study, which is considerably smaller (3.7 * 10^4 km^2 between 16° and 21° N), yields 3.4 Gg N yr^{-1}. Thus, *Nevison et al.*'s [2004] estimate appears to be considerably higher than our estimate. However, there are two caveats associated with their estimate: 1) For the computation of k_w, *Nevison et al.* [2004] applied the air-sea gas exchange approach of *Wanninkhof* [1992] which generally yields k_w significantly higher than those computed with *Nightingale et al.*'s [2000] approach used in our study. Using *Nightingale et al.*'s [2000] approach is in agreement with recent studies, which suggest that *Wanninkhof*'s [1992] relationship is overestimating k_w by 33% [*Wanninkhof et al.*, 2009]. 2) Because of missing data, *Nevison et al.* [2004] had to estimate N_2O in 100 m with an empirical N_2O/O_2 relationship and they explicitly state that their estimate may be associated with an error of ±30%. Thus, we conclude that *Nevison et al.*'s [2004] estimate is overestimated.

[10] Despite the fact that the Mauritanian upwelling area considered in our study represents about 2% of the global coastal upwelling (1.75 * 10^6 km^2 as given by *Nevison et al.* [2004]), its N_2O emissions contribute only about 0.5%

(corrected: 0.3%) of the global N_2O upwelling emissions of $200 \pm >140$ Gg N yr^{-1} [*Nevison et al.*, 2004]. Therefore, we conclude that N_2O emissions from the Mauritanian upwelling are only of minor importance for the atmospheric N_2O budget and they do not represent a globally significant 'hot spot' of N_2O emissions. Thus, in view of its N_2O emissions, the Mauritanian upwelling is different from other major coastal upwelling areas, such as those found in the Arabian Sea or off Chile [*Naqvi et al.*, 2005; *Paulmier et al.*, 2008]. For example, N_2O emissions along the coast of the Arabian Peninsula have been estimated to range from 47–90 Gg N during the upwelling period [*Bange et al.*, 1996b]. One reason for the comparatively low total N_2O emissions from off Mauritania is the fact that the subsurface oxygen minimum zone (OMZ) off Mauritania is not suboxic, i.e., the O_2 concentrations are always >40 μmol L^{-1} [*Karstensen et al.*, 2008; *Naqvi et al.*, 2009]. Suboxic conditions, however, would favor accumulation of N_2O in subsurface layers via enhanced nitrification and/or denitrification [*Bange*, 2008]. This, in turn, can result in very high N_2O emissions as have been shown only recently for the upwelling off Chile [*Paulmier et al.*, 2008].

5. Summary

[11] N_2O flux densities across the ocean/atmosphere interface from the Mauritanian upwelling (16°–21°N) were computed using the "wind-only" upwelling model approach of *Nevison et al.* [2004]. N_2O measurements from four cruises between 2006 and 2008 as well as winds from the QuikSCAT satellite were used as input data. The resulting N_2O flux densities showed a strong seasonality, reflecting the wind-driven seasonality of the upwelling off Mauritania: computed N_2O flux densities are highest in the northern part (19.5°–21°N) and show a decreasing trend towards the south. The summer periods with no upwelling (and thus resulting in no or negligible N_2O fluxes densities) are most pronounced in the southern part (16°–17°N). The mean total N_2O emissions from the Mauritanian upwelling were estimated to 1.0 Gg N yr^{-1} indicating that N_2O emissions from the Mauritanian upwelling are only of minor importance for the atmospheric N_2O budget.

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