

Quantifying the impact of anthropogenic nitrogen deposition on oceanic nitrous oxide

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[1] Anthropogenically induced increases in nitrogen deposition to the ocean can stimulate marine productivity and oceanic emission of nitrous oxide. We present the first global ocean model assessment of the impact on marine N₂O of increases in nitrogen deposition from the pre-industrial era to the present. We find significant regional increases in marine N₂O production downwind of continental outflow, in coastal and inland seas (15–30%), and nitrogen limited regions of the North Atlantic and North Pacific (5–20%). The largest changes occur in the northern Indian Ocean (up to 50%) resulting from a combination of high deposition fluxes and enhanced N₂O production pathways in local hypoxic zones. Oceanic regions relatively unaffected by anthropogenic nitrogen deposition indicate much smaller changes (<2%). The estimated change in oceanic N₂O source on a global scale is modest (0.08–0.34 Tg N yr⁻¹, ~3–4% of the total ocean source), and consistent with the estimated impact on global export production (~4%). **Citation:** Suntharalingam, P., E. Buitenhuis, C. Le Quéré, F. Dentener, C. Nevison, J. H. Butler, H. W. Bange, and G. Forster (2012), Quantifying the impact of anthropogenic nitrogen deposition on oceanic nitrous oxide, *Geophys. Res. Lett.*, 39, L07605, doi:10.1029/2011GL050778.

1. Introduction

[2] Intensification of fossil fuel combustion and nitrogenous fertilizer application since the pre-industrial era has increased global emissions of inorganic reactive nitrogen (primarily nitrogen oxides and ammonia species (NO_y + NH_x)), and associated atmospheric nitrogen deposition on the ocean [Duce *et al.*, 1991; Dentener *et al.*, 2006]. This flux to the ocean provides a supplemental nutrient source to marine ecosystems in nitrogen limited regions, with potential for significant impacts on productivity, ocean pH, and ocean–atmosphere fluxes of greenhouse gases such as N₂O [Prospero *et al.*, 1996; Krishnamurthy *et al.*, 2007; Doney *et al.*, 2007; Duce *et al.*, 2008]. N₂O is the third most significant contributor to radiative forcing of the long-lived

greenhouse gases [Forster *et al.*, 2007], and current emissions, weighted by ozone depleting potential, are now estimated to exceed those of other ozone depleting agents [Ravishankara *et al.*, 2009].

[3] NH_x and NO_y have atmospheric lifetimes of hours to days and can be transported over large spatial scales (10²–10³ km); Dentener *et al.* [2006] estimate that over 80% of current oceanic deposition of these species occurs over the open ocean, with the remainder on coastal and shelf regions. Present-day levels of total reactive nitrogen (Nr) deposition on the ocean are estimated to be 38–96 Tg N yr⁻¹ [Duce *et al.*, 2008, hereinafter D2008]. This flux is comparable to other external nitrogen inputs to the upper ocean; c.f., 60–200 Tg N yr⁻¹ from marine nitrogen fixation [Gruber, 2008], and 50–80 Tg N yr⁻¹ from river input [Galloway *et al.*, 2004; Seitzinger *et al.*, 2005].

[4] The anthropogenic component of this deposition flux to the ocean has increased almost ten-fold since 1860, to ~54 (31–77) Tg N yr⁻¹ in 2000. It is estimated to account for ~3% of current global oceanic export production (~0.31 (0.18–0.44) Pg C yr⁻¹ (D2008)). D2008 also highlight the potential impact on oceanic N₂O evolution and suggest that increases in atmospheric nitrogen deposition since 1860 could account for a third (~1.6 Tg N yr⁻¹) of present-day ocean N₂O emissions, with likely increases over the coming decades. Oceanic N₂O is formed during the sub-surface remineralization of organic matter. The dominant formation pathway in well-oxygenated environments is believed to be nitrification during the oxidation of ammonium to nitrate [Cohen and Gordon, 1979; Frame and Casciotti, 2010; Santoro *et al.*, 2011, and references therein]. However, N₂O cycling mechanisms display sensitivity to local oxygen level; higher yields are noted at low O₂ levels, ascribed to alternate source pathways such as enhanced nitrification, denitrification, and interactions between the two [Codispoti *et al.*, 2001; Naqvi *et al.*, 2000]. Denitrification in anoxic regions can also provide a sink for N₂O. Marine sub-oxic zones, such as those in the Eastern Tropical Pacific and the Arabian Sea, are important net sources of N₂O to the atmosphere [Bange *et al.*, 2001; Naqvi *et al.*, 2010], and potentially contribute a significant portion (25–50%) of global ocean emissions [Codispoti, 2010]. Increases in anthropogenic nitrogen input to these regions is predicted to intensify local N₂O formation and the ocean-to-atmosphere flux [Naqvi *et al.*, 2000; Bange *et al.*, 2010].

[5] Ocean biogeochemistry model analyses have assessed the impact of increased Nr deposition on marine productivity [Krishnamurthy *et al.*, 2007] and ocean acidification [Doney *et al.*, 2007], and report a spatially varied response with noted coastal amplification. The response of the marine N₂O cycle, however, has not been investigated in similar detail.

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Table 1. Impact of Change in Nr Deposition on Oceanic N₂O Source: Summary of Results for the N₂O Simulations^a

Simulation	α (mol/mol)	β (mol/mol)	Global Ocean N ₂ O Source 'Background' Deposition (Tg N yr ⁻¹)	Global Ocean N ₂ O Source 'Year 2000' Deposition (Tg N yr ⁻¹)	Change in N ₂ O Source = Difference of 'Year 2000' and 'Background' Simulations (Tg N yr ⁻¹)
Standard	0.75×10^{-4}	0.01	4.42	4.57	0.15
<i>Sensitivity Simulations^b</i>					
NitrificationOnly_0.75	0.75×10^{-4}	0	2.97	3.05	0.08
NitrificationOnly_0.5	0.5×10^{-4}	0	1.98	2.04	0.06
NitrificationOnly_1.0	1.0×10^{-4}	0	3.96	4.07	0.11
LowO2x2	0.75×10^{-4}	0.02	5.86	6.08	0.22
LowO2x3	0.75×10^{-4}	0.03	7.31	7.59	0.28
LowO2x4	0.75×10^{-4}	0.04	8.76	9.10	0.34
Nevison_2003 ^c			5.95	6.25	0.30

^aGlobal oceanic N₂O source for 'Background' and 'Year 2000' deposition scenarios (columns 4 and 5); model estimated impact of anthropogenic Nr deposition on oceanic N₂O production (column 6).

^bThe 'NitrificationOnly' and 'LowO2' sensitivity simulations use variations of the N₂O source parameterization of equation (1), with different values of α and β , to change the weighting on the 'Nitrification' and 'Low-oxygen' N₂O source pathways.

^cThe 'Nevison_2003' simulation implements the N₂O source parameterization of *Nevison et al.* [2003].

Previous estimates of the impact of anthropogenic Nr deposition on marine N₂O have been derived from simple scaling analyses (e.g., D2008). Here, we use a global ocean biogeochemistry model, which includes representation of the N₂O cycle, to quantify the impact of the increases in reactive nitrogen deposition on ocean biogeochemistry and specifically on the marine N₂O source. This is the first spatially resolved analysis of this impact on marine N₂O, and enables us to identify sensitive regions where anthropogenic deposition has the most significant influence on marine N₂O formation.

2. Methods and Model Configuration

2.1. Ocean Biogeochemistry Model

[6] We use the PlankTOM5 ocean biogeochemistry model [*Le Quéré et al.*, 2005; *Vogt et al.*, 2010], embedded in the prognostic global ocean general circulation model NEMO v2.3 [*Madec et al.*, 1999], and forced by daily meteorological data from the NCEP reanalysis. PlankTOM5 combines a representation of ecosystem dynamics, based on five plankton groups, with ocean biogeochemistry parameterizations from the PISCES model [*Aumont and Bopp*, 2006]. The model is run at a horizontal resolution of $\sim 2^\circ$ with higher resolution (up to 0.5°) in tropical and polar latitudes, and 31 vertical levels with 10 m resolution in the upper 100 m. Model global export production is 9.5 Pg C yr^{-1} , consistent with recent estimates ($9\text{--}12 \text{ Pg C yr}^{-1}$) [*Schlitzer*, 2002], $3\text{--}20 \text{ Pg C yr}^{-1}$ [*Najjar et al.*, 2007]). Additional details on model configuration and evaluation are given by *Cotrim da Cunha et al.* [2007] and *Vogt et al.* [2010].

2.2. N₂O Model

[7] NEMO-PlankTOM5 has been extended to simulate the N₂O cycle, based on the parameterization of *Suntharalingam et al.* [2000], which relates N₂O production to marine organic matter remineralization via the oxygen consumption rate:

$$\text{N}_2\text{O Source} = \alpha \cdot [\text{Oxygen Consumption Rate}] + \beta \cdot f(\text{O}_2) \cdot [\text{Oxygen Consumption Rate}] \quad (1)$$

The two terms account for separate formation pathways representing (i) nitrification in the oxygenated ocean, and (ii)

the enhanced yield of N₂O at low oxygen levels. α is a scalar multiplier derived from observed correlations between $\Delta\text{N}_2\text{O}$ ('excess N₂O') and Apparent Oxygen Utilization (AOU) [*Suntharalingam and Sarmiento*, 2000]. The parameterization of the high-yield N₂O source in low oxygen zones follows the methods of *Suntharalingam et al.* [2000], where β is a linear scaling parameter, and $f(\text{O}_2)$ accounts for the functional dependence of N₂O yield on oxygen level. N₂O loss by denitrification is represented at oxygen levels below $5 \mu\text{mol/L}$ [*Friederich et al.*, 1985].

[8] Our 'Standard' simulation uses values $\alpha = 0.75 \times 10^{-4} \text{ mol/mol}$ and $\beta = 0.01 \text{ mol/mol}$. We also evaluate a set of sensitivity simulations (Table 1) varying the values of α and β to account for reported regional variation in N₂O yield in oxic and sub-oxic waters [*Law and Owens*, 1990; *Freitag et al.*, 2009]). We evaluate, as an additional sensitivity, the parameterization of *Nevison et al.* [2003], which additionally accounts for the influence of water-mass mixing on measurements of AOU and $\Delta\text{N}_2\text{O}$. The primary aim of the sensitivity analyses is to characterize the uncertainty in the N₂O source function, when estimating the impact of anthropogenic Nr deposition on marine N₂O.

[9] Our N₂O simulations have been evaluated with a compilation of oceanic measurements from the cruises listed in Text S1 in the auxiliary material.¹ Figure S1 presents a comparison of model sensitivity simulations (Table 1) against N₂O measurements for different oceanic regions characterizing both oxygenated (North and South Atlantic, Western Pacific), and low-oxygen zones (Eastern Equatorial Pacific, Arabian Sea). The 'Standard' and the 'Nevison2003' model simulations, sampled at the measurement locations, provide the best match to the observations capturing the magnitude and depth of the observed sub-surface N₂O maximum in the majority of the regions. We note that both 'Standard' and the 'Nevison2003' simulations overestimate observed N₂O in the Arabian Sea; this results from a poor representation of the local monsoonal upwelling and associated biogeochemical fluxes in coarse grid ocean models [*Aumont and Bopp*, 2006; *Suntharalingam and Sarmiento*, 2000]. The global oceanic N₂O source in the 'Standard'

¹Auxiliary materials are available in the HTML. doi:10.1029/2011GL050778.

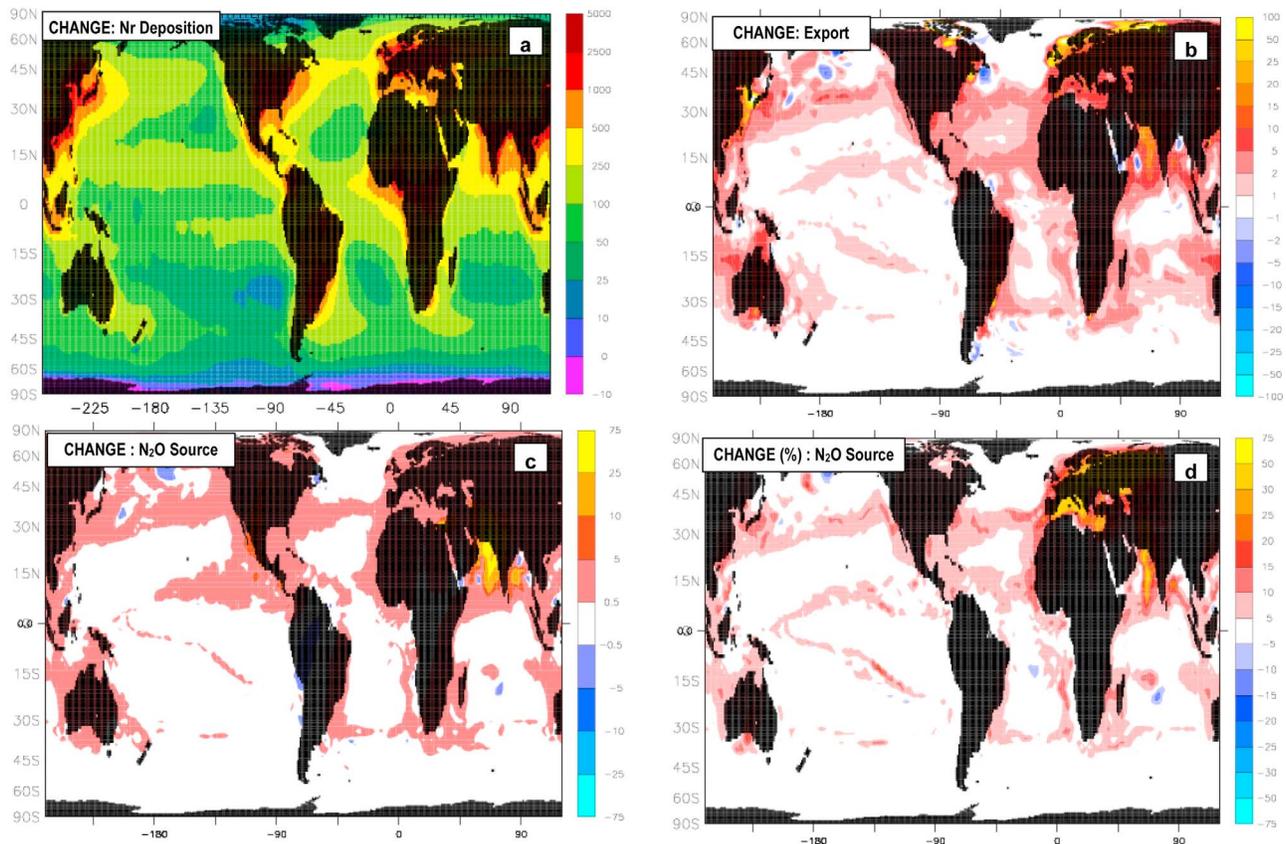


Figure 1. (a) Change in reactive nitrogen deposition; $\Delta\text{Nr Deposition} = \text{‘Year 2000’} \text{ minus ‘Background’}$ deposition distributions. (Units : $\text{mg N m}^{-2} \text{ yr}^{-1}$). Data sources: *Duce et al.* [2008]; *Dentener et al.* [2006]; gridded distributions provided by K. Altieri (personal communication, 2009). (b) Change in organic carbon export estimated from NEMO-PlankTOM5 model (Units : $\text{g C m}^{-2} \text{ yr}^{-1}$); $\Delta\text{C Export} = \text{Difference between ocean model simulations forced with ‘Year 2000’ and ‘Background’}$ Nr deposition distributions. (c) Change in oceanic N₂O production (column integral, Units : $\text{mg N m}^{-2} \text{ yr}^{-1}$); $\Delta\text{N}_2\text{O Source} = \text{Difference between ocean model simulations forced with ‘Year 2000’ and ‘Background’}$ Nr deposition distributions (for the ‘Standard’ N₂O simulation). (d) Percentage change in oceanic N₂O production (Units : % change in column integral); $\Delta\text{N}_2\text{O Source}$ expressed as a percentage of the ocean N₂O source for the ‘Background’ scenario (‘Standard’ N₂O model simulation).

simulation is 4.6 Tg N yr^{-1} (comprised of 3.0 Tg N yr^{-1} from the ‘nitrification’ pathway, and 1.6 Tg N yr^{-1} from the low-oxygen pathway). The sensitivity simulations yield an oceanic N₂O source range of $2.0\text{--}9.1 \text{ Tg N yr}^{-1}$ (Table 1), consistent with recent estimates ($1.8\text{--}5.8 \text{ Tg N yr}^{-1}$ [Denman et al., 2007], and $3\text{--}11 \text{ Tg N yr}^{-1}$ [Bange, 2006]).

2.3. Nitrogen Deposition Simulations

[10] For all the simulations discussed in this analysis, we force the NEMO-PlankTOM5 model with a climatological meteorology (NCEP decadal average for 1996–2005) to minimize the influence of inter-annual meteorological variation, as our primary aim is evaluation of the impact of the change in anthropogenic Nr deposition on marine N₂O through the assessment of different deposition scenarios. The inorganic carbon system tracers were initialized using the Global Ocean Data Analysis Project (GLODAP) [Key et al., 2004], macro-nutrient initialization is from the World Ocean Atlas [Garcia et al., 2006], and the other biological variables were initialized with values from a previously equilibrated model run [Vogt et al., 2010]. For the sensitivity analyses presented here, the ocean model

was run for a further 60 years, and we report averaged values from the last decade of these simulations.

[11] Atmospheric Nr deposition fluxes are taken from D2008 ($1^\circ \times 1^\circ$ gridded fields provided by K. Altieri (personal communication, 2009)), and account for inorganic and organic reactive nitrogen. We implement separate deposition distributions for (i) pre-industrial (‘Background’), and (ii) present-day (‘Year 2000’), conditions, with global Nr deposition totals on the ocean of $13.3 \text{ Tg N yr}^{-1}$ and 67 Tg N yr^{-1} respectively (D2008). The change in Nr deposition between these scenarios is illustrated in Figure 1a, and indicates significant increases in coastal and inland seas downwind of populated regions of East Asia, North America, the Indian sub-continent, and Western Europe. The largest open-ocean change occurs in the northern Indian Ocean (up to a ten-fold increase). Open-ocean gyre regions of the North Atlantic and North Pacific indicate two to five-fold increases (D2008).

[12] We evaluate the impact of anthropogenic Nr deposition on the marine N₂O source using the difference between two ocean model simulations, one subject to a pre-industrial ‘Background’ level of Nr deposition, and one with Nr

deposition levels for ‘Year 2000’; this follows similar methodology to previous such evaluations [Krishnamurthy *et al.*, 2007; Doney *et al.*, 2007].

3. Results

[13] Our model estimate of the impact of anthropogenic Nr deposition on global export production is 0.4 Pg C yr⁻¹ (~4% of global export); this is derived as the difference in export between ‘Background’ (9.5 Pg C yr⁻¹) and ‘Year2000’ (9.9 Pg C yr⁻¹) simulations. This estimate is comparable to those of recent investigations: 0.31 (0.18–0.44) Pg C year⁻¹ (D2008), and 0.2 Pg C yr⁻¹ [Krishnamurthy *et al.*, 2007] (for a lower present-day Nr deposition flux of 47 Tg N yr⁻¹). The spatial distribution of the impact on export (Figure 1b) indicates largest changes in regions of high anthropogenic Nr deposition; specifically, coastal oceans (export increases >30%), the northern Indian ocean (up to 50%), and nitrate-depleted regions of northern hemispheric ocean basins (10–20%). Regions relatively unaffected by polluted continental outflow (e.g., much of the Southern Hemisphere) show export changes of less than 2%.

[14] Figures 1c and 1d illustrate the distribution of absolute and proportionate (in %) change in column-integrated N₂O source for the ‘Background’ to ‘Year 2000’ change in Nr deposition (‘Standard’ N₂O simulation shown). They indicate significant increases in N₂O production in regions of high Nr deposition, e.g., coastal and inland seas (15–30%), and North Atlantic and North Pacific basin regions downwind of continental outflow (5–20%). The largest impact is associated with the oceanic low oxygen zone of the Arabian Sea, where high levels of Nr deposition coincide with the dominant influence of the enhanced-yield N₂O source pathway. N₂O production in the 300–1000 m depth range of the low-oxygen zone of the Arabian Sea increases by ~50%.

[15] These local impacts correspond to measurable changes in the water column concentration of N₂O; largest changes are associated with low oxygen regions, e.g., 2–2.5 nmol L⁻¹ for the 100–300 m depth range in the Eastern Equatorial Pacific, and 5–6 nmol L⁻¹ in the 200–500 m range of the Arabian Sea. Smaller, but still detectable changes occur in oxygenated waters, in particular, immediately downwind of continental outflow, e.g., 0.4–0.5 nmol L⁻¹ in the 200–500 m depth range of the western North Atlantic downwind of the outflow from the North American continent; and 0.3–0.4 nmol L⁻¹ at 400–700 m depth in the Western Pacific downwind of Asian outflow. We use as our criteria for detection limits the values reported by *Upstill-Goddard et al.* [1996] of ~40 picomol L⁻¹.

[16] Table 1 summarizes the global results for the N₂O sensitivity simulations; the increase in net marine N₂O production ranges between 0.06–0.34 Tg Nyr⁻¹, representing a 3–4% change in the global ocean source. This estimate of impact on global N₂O production is smaller than that suggested by D2008 (~1.6 (1.2–2.0) Tg Nyr⁻¹). Our model estimate of the impact on export production (0.4 Pg C yr⁻¹), however, is of comparable magnitude to that of D2008 of 0.18–0.44 Pg C yr⁻¹. The discrepancy in estimated impact on N₂O between our global model result and that of D2008 arises from the differing underlying methods. In our model simulations, the main determinants of the marine N₂O

source are (i) the magnitude of organic matter remineralization in the aphotic zone (primarily driven by organic carbon export), and (ii) the local oxygen level. A change imposed on sub-surface organic matter remineralization (i.e., via a change in export due to increased Nr deposition) induces an associated change in N₂O formation. Our estimate of the impact of anthropogenic Nr deposition on N₂O source is based on this change in organic matter remineralization (between the ‘Background’ and ‘Year 2000’ simulations), and is stoichiometrically consistent with the impact on export.

[17] The impact on N₂O of D2008 is derived from a global scaling of nitrogen fluxes [Duce *et al.*, 2008, Table S1]. This scaling estimates the contribution of anthropogenic Nr to oceanic N₂O emission by multiplying the global ocean N₂O flux (5.0 Tg Nyr⁻¹ by D2008) by a scaling factor which accounts for the proportionate contribution of anthropogenic Nr deposition (54 Tg Nyr⁻¹) to the external inputs of ‘new nitrogen’ fuelling surface ocean productivity. D2008 define this ‘new nitrogen’ as the sum of nitrogen deposition and nitrogen fixation (totalling 167 Tg Nyr⁻¹). The ratio of anthropogenic Nr deposition to this ‘new nitrogen’ total yields a scaling factor of ~0.32, and their estimate of the impact on oceanic N₂O of 1.6 Tg Nyr⁻¹. This scaling analysis, however, neglects the supply of ‘new’ nitrate upwelled from below (~1200 Tg N yr⁻¹ [Gruber, 2008]), which is relevant on the decadal to century timescales of anthropogenic Nr increase. If we modify the methodology of D2008 to account for this upwelling nitrate flux (by including this term in column 4 of Table S1 of D2008), the modified scaling factor becomes ~0.04, yielding an impact on oceanic N₂O of 0.19 Tg Nyr⁻¹; this is consistent with our model estimated range of 0.06–0.34 Tg N yr⁻¹.

[18] We are not aware of any other quantification of the impact of Nr deposition on the global oceanic N₂O source. *Galloway et al.* [2004, Table 3 and Figure 1] estimate a change of 0.4 Tg N yr⁻¹ in estuarine and shelf N₂O emissions due to anthropogenic reactive nitrogen impacts between 1860 and the 1990s; they assume, however, that the open ocean N₂O source remains constant (at 3.5 Tg N yr⁻¹) in this timeframe.

4. Uncertainties

[19] Potential uncertainties in our global model estimate could arise from uncertainties in the underlying parameterizations (for N₂O, ocean biogeochemistry and circulation), and in our assumptions on Nr assimilation by marine organisms. We note, firstly, that our methodology is designed to minimize the impact of systematic model biases (e.g., in circulation or biogeochemistry), as it relies on the difference between two simulations, that differ only in their surface deposition flux of Nr.

[20] Our model estimate of the impact of anthropogenic Nr deposition on export (0.4 Pg C yr⁻¹) is similar to that of D2008 and *Krishnamurthy et al.* [2007] (0.18–0.44 Pg C yr⁻¹), and therefore unlikely to be a cause of error in the N₂O source estimate. Our N₂O sensitivity simulations (Table 1) are designed to characterize uncertainty in the parameterization of the marine N₂O source. The ‘Standard’ and ‘Nevison2003’ simulations produce the closest match to the observations on a global scale (Figure S1). The extreme low and high N₂O scenarios

characterize a range of simulated oceanic N₂O distributions; e.g., the ‘NitrificationOnly’ simulations underestimate, and the ‘LowO2x2’ to ‘LowO2x4’ simulations overestimate observed N₂O throughout the water column. In this context, the impact on marine N₂O associated with the ‘LowO2x2’ to ‘LowO2x4’ simulations (0.22–0.34 Tg N yr⁻¹) can be considered an upper bound. Our model analysis also assumes complete assimilation of the deposited Nr by ecosystems in nitrogen limited regions. However, components of the deposition Nr flux (e.g., water-soluble organic nitrogen [Cornell *et al.*, 2003]) may not be immediately bio-available; in this context, our model estimates must also be regarded as an upper bound.

[21] Our analysis, and that of D2008, estimate the impact of the nutrient fertilization on N₂O evolution with a link to enhanced marine productivity. In-situ iron fertilization experiments have reported contrasting results with regard to N₂O; increases in sub-surface N₂O saturation were observed during the Southern Ocean Iron Release Experiment (SOL-REE) [Law and Ling, 2001], but not during the European Iron Fertilization Experiments (EIFEX), possibly due to rapid sedimentation of resulting particulate matter in the latter [Walter *et al.*, 2005]. Additional monitoring of the fate of the export particulate phase is called for to resolve this impact on N₂O [Law, 2008]. In view of a potentially diminished role for nutrient fertilization, our model estimates again constitute an upper bound on N₂O evolution from Nr deposition.

[22] Beman *et al.* [2010] note a lowering of marine ammonia oxidation rates with decreasing pH (3–44% for a pH change of 0.1) and suggest associated reductions in the oceanic nitrification source of N₂O with increasing ocean acidification. A detailed evaluation of the impact of the increases in ocean acidification since the pre-industrial era is beyond the scope of this study, however, in view of the potential decrease in nitrification rates [Beman *et al.*, 2010], which is not represented in our analysis, our model estimates again provide an upper bound on the impact of Nr deposition on N₂O evolution. Uncertainty in the model oxygen distribution is a potential source of error [Najjar *et al.*, 2007], as local oxygen levels determine the magnitude and distribution of the high-yield N₂O source pathway. In the simulations of Table 1, we minimize this potential error by holding model oxygen distributions to the climatological values of World Ocean Atlas [Garcia *et al.*, 2006]. This approach, however, also limits the capability for simulating biogeochemical feedbacks between oxygen and N₂O, as the model’s oxygen distribution, being fixed to the observed values, does not reflect the production and consumption resulting from organic matter formation and remineralization. We have therefore conducted additional sensitivity simulations (parallel to those of Table 1), where model oxygen is allowed to change, and no longer fixed to the WOA climatology. These indicate that this feedback effect on oxygen and N₂O yield is relatively small, accounting for an additional change of less than 0.01 Tg N yr⁻¹.

5. Summary

[23] We have evaluated the impact on the marine N₂O source of the increase in anthropogenic reactive nitrogen deposition from the pre-industrial era to the present day using a global ocean biogeochemistry model. Our analyses

indicate relatively modest increases in the oceanic N₂O source on a global scale (0.06–0.34 Tg N yr⁻¹). This is equivalent to a 3–4% change in the global ocean N₂O source, and consistent with the proportional impact on export production (~4%). Our estimate for N₂O is lower than that suggested by a recent study (D2008); the discrepancy arises from the scaling methodology of D2008, which did not account for the upwelling flux of new nitrogen in their analysis. Inclusion of the flux of upwelled nitrogen in the method of D2008 yields a result of similar magnitude to our global model estimates.

[24] Our model analysis indicates significant regional impacts, however, downwind of populated zones, particularly in coastal and inland seas, in nitrogen limited regions of the North Atlantic and North Pacific, and the northern Indian Ocean. The Arabian Sea demonstrates the largest change, with regional source increases of ~50%. This results from high anthropogenic Nr deposition fluxes stimulating productivity over the hypoxic zones associated with enhanced N₂O formation, and illustrates the potential sensitivity of such low-oxygen zones to changes in surface nutrient forcing. Quantifying the impact on N₂O in such regions should be a priority for future investigations.

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