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Key Points:
- Uncertainties in marine N_2O emissions are quantified
- The largest uncertainty in marine N_2O emissions is surface N_2O production

Supporting Information:
- Readme
- Text S1

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Surface nitrification: A major uncertainty in marine N_2O emissions

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Abstract The ocean is responsible for up to a third of total global nitrous oxide (N_2O) emissions, but uncertainties in emission rates of this potent greenhouse gas are high (>100%). Here we use a marine biogeochemical model to assess six major uncertainties in estimates of N_2O production, thereby providing guidance in how future studies may most effectively reduce uncertainties in current and future marine N_2O emissions. Potential surface N_2O production from nitrification causes the largest uncertainty in N_2O emissions (estimated up to ~1.6 Tg N yr^{-1} or 48% of modeled values), followed by the unknown oxygen concentration at which N_2O production switches to N_2O consumption (0.8 Tg N yr^{-1} or 24% of modeled values). Other uncertainties are minor, cumulatively changing regional emissions by <15%. If production of N_2O by surface nitrification could be ruled out in future studies, uncertainties in marine N_2O emissions would be halved.

1. Introduction

Oceanic nitrous oxide (N_2O) emissions contribute 10–30% of tropospheric N_2O concentrations, but uncertainties in these emissions are >100% [*Ciais et al.*, 2013]. The largest oceanic N_2O emissions are observed in high-productivity low-oxygen (O_2) regions such as the Eastern Tropical Pacific (ETP) [*Nevison et al.*, 1995]. The microbial processes that mediate subsurface marine N_2O production and consumption (nitrification and denitrification) are primarily constrained by biological activity and O_2 concentrations. The highest N_2O production and consumption rates occur at low O_2 levels (~1–15 μM) that are difficult to measure and even more difficult to model, making it difficult to give reliable predictions of how future-predicted deoxygenation in regions like the ETP will affect regional N_2O emissions [*Zamora et al.*, 2012].

Further uncertainty unaccounted for in the above estimates arises from recent work suggesting that N_2O may also be produced in surface waters. Surface N_2O production from bacteria was previously ruled out due to excessive light [*Ward*, 2008] and oxygen, a denitrification inhibitor [*Averill and Tiedje*, 1982]. However, active *archaeal* ammonia oxidation has recently been observed in the ETP euphotic zone [*Church et al.*, 2010; *Beman et al.*, 2012] and other regions [e.g., *Ward*, 2005; *Grundle et al.*, 2013]. As *Archaea* can produce N_2O during ammonia oxidation [*Santoro et al.*, 2011; *Löscher et al.*, 2012], it has been suggested that N_2O may also be produced in the upper euphotic zone [*Charpentier et al.*, 2010].

There is N_2O production in the lower photic zone (~100–150 m) of the North Pacific [*Dore and Karl*, 1996; *Dore et al.*, 1998; *Popp et al.*, 2002], but currently, there is no direct evidence of N_2O production in the upper 100 m (the region most important for air-sea gas exchange). However, upper 100 m N_2O production could explain discrepancies between low subsurface diapycnal N_2O flux and high air-sea N_2O flux in the South Pacific, Caribbean, and eastern tropical Atlantic [*Morell et al.*, 2001; *Charpentier et al.*, 2010; *Kock et al.*, 2012]. It might also contribute to why models cannot reproduce the anomalously early seasonal peak in ventilated Southern Ocean N_2O [*Nevison et al.*, 2012].

To date, there has been incomplete systematic testing of the various uncertainties in marine N_2O emissions (including N_2O production and consumption rates, their dependence on oxygen concentrations, and the potential for N_2O production by surface nitrification). Here we examine the sensitivity of N_2O emissions to uncertainties in six marine N_2O parameterizations, with a focus on the ETP. Our goals are to quantitatively estimate current uncertainties in marine N_2O emissions and to provide guidelines for where future research should focus in order to reduce uncertainties and improve projections of future N_2O emissions.

Table 1. Overview of Parameters and Values Tested

Abbreviation	Parameter	Values Tested	Baseline Scenario	Units
SW[a]	O_2 concentration at which net N_2O production changes to net N_2O consumption	1, 4, 10, and 15	4	μM O_2
CR[a]	N_2O consumption rate at low O_2	0.01, 0.1, and 1	0.1	mmol N_2O m^{-3} yr^{-1}
SSP	Net subsurface N_2O production as a function of O_2	linear[a] and nonlinear[b]	linear	not applicable (na)
SP	Net surface N_2O production from nitrification[c]	0[d], 1, 10, and 50	0	% produced surface NH_4^+ nitrified
SOV	Suboxic volume for the ETP[e]	6.9 and 4.4[f]	6.9	$\times 10^{15}$ m^3
AD	Atmospheric inorganic nitrogen deposition	not present[g] and present[h]	not present	na

[a] *Zamora et al.* [2012].
[b] *Suntharalingam et al.* [2000], equation (3).
[c] Assuming the same amount of N_2O produced during nitrification as in the subsurface.
[d] *Suntharalingam and Sarmiento* [2000], *Suntharalingam et al.* [2000], *Suntharalingam et al.* [2012], *Jin and Gruber* [2003], *Nevison et al.* [2003], *Schmittner et al.* [2008], *Dutreuil et al.* [2009], *Bianchi et al.* [2012], *Manizza et al.* [2012], *Zamora et al.* [2012], *Gutknecht et al.* [2013], and *Saikawa et al.* [2014].
[e] Suboxic is defined as ≤10 μM O_2. ETP is defined as the region in Figure 1.
[f] *Getzlaff and Dietze* [2013].
[g] Same as in label d, not including *Suntharalingam et al.* [2012].
[h] Deposition was added here similarly to *Suntharalingam et al.* [2012] but using inorganic nitrogen deposition from the CAM version 3.5 [*Lamarque et al.*, 2011].

2. Methods

N_2O data were obtained from the MEMENTO database following *Zamora et al.* [2012]. Gridded oxygen values were obtained from the corrected World Ocean Atlas 2005 [*Bianchi et al.*, 2012]. N_2O fluxes from the ocean to the atmosphere were calculated following *Nevison et al.* [1995] and using the Comprehensive Ocean-Atmosphere Data Set monthly long-term mean surface wind speeds [*da Silva et al.*, 1994], corresponding to the location and month of each MEMENTO surface N_2O sample. Salinity and temperature used in determining solubility were generally measured alongside N_2O and are recorded in the MEMENTO database [see *Zamora et al.*, 2012]; however, for some stations, salinity was not recorded. In these instances, the nearest salinity values from the World Ocean Atlas 2009 [*Antonov et al.*, 2010] were used (errors resulting from this approximation are expected to be negligible). Historic atmospheric N_2O concentrations at the year of sampling were calculated from *Meinshausen et al.* [2011].

Model sensitivity analyses were conducted with the University of Victoria (UVic) Earth System Climate Model [*Eby et al.*, 2009] version 2.9 with modifications from *Keller et al.* [2012]. The model was spun up following *Zamora et al.* [2012], running historic atmospheric N_2O and CO_2 concentrations from *Meinshausen et al.* [2011] up to the year 2008. We used the UVic model to assess the sensitivity of N_2O emissions to six parameters (described in Table 1). Several of these parameters were heavily dependent upon O_2 concentrations, and therefore, we provide a description of model performance for O_2 and N_2O in the Supplement. Atmospheric inorganic nitrogen deposition estimates from 1850 to 2000 were applied from the National Center for Atmospheric Research-Community Atmosphere Model (CAM) version 3.5 [*Lamarque et al.*, 2011] (values for individual years were interpolated from the decadal data provided). Values from 2001 to 2008 were provided from their Representative Concentration Pathway (RCP) 8.5 scenario.

When available, we tested the range of published literature values for each parameter (Table 1). Our assessment of the potential importance of surface nitrification for N_2O production was hindered by two major uncertainties: (1) surface nitrification rates and (2) N_2O production rates from surface nitrification. Surface nitrification rates vary widely [*Clark et al.*, 2008], and nitrifiers can assimilate up to 33% of surface-regenerated NH_4^+ [*Yool et al.*, 2007]. Reasons for variability in surface nitrification rates are not well known, and so we assumed that a constant fraction of regenerated N would be nitrified in each sensitivity experiment (between 0 and 50%; see Table 1 and the Supplement). This wide range in surface nitrification rate scenarios was chosen in order to bracket the observed rates [*Yool et al.*, 2007]. Although several studies have linked surface ammonium oxidation rates with light levels [*Grundle et al.*, 2013; *Ward*, 2005], we did not include light as a determinant of surface nitrification, because so far, evidence does not support light being the dominant factor controlling surface nitrification [*Ward*, 2005], and the causal relationship between the two is still uncertain.

To describe N_2O production rates in the surface, we made a second major assumption: that there are similar relationships between nitrification-derived N_2O production and O_2 consumption in the surface and subsurface (we used the subsurface relationship described by *Zamora et al.* [2012]; see the Supplement). Given that the

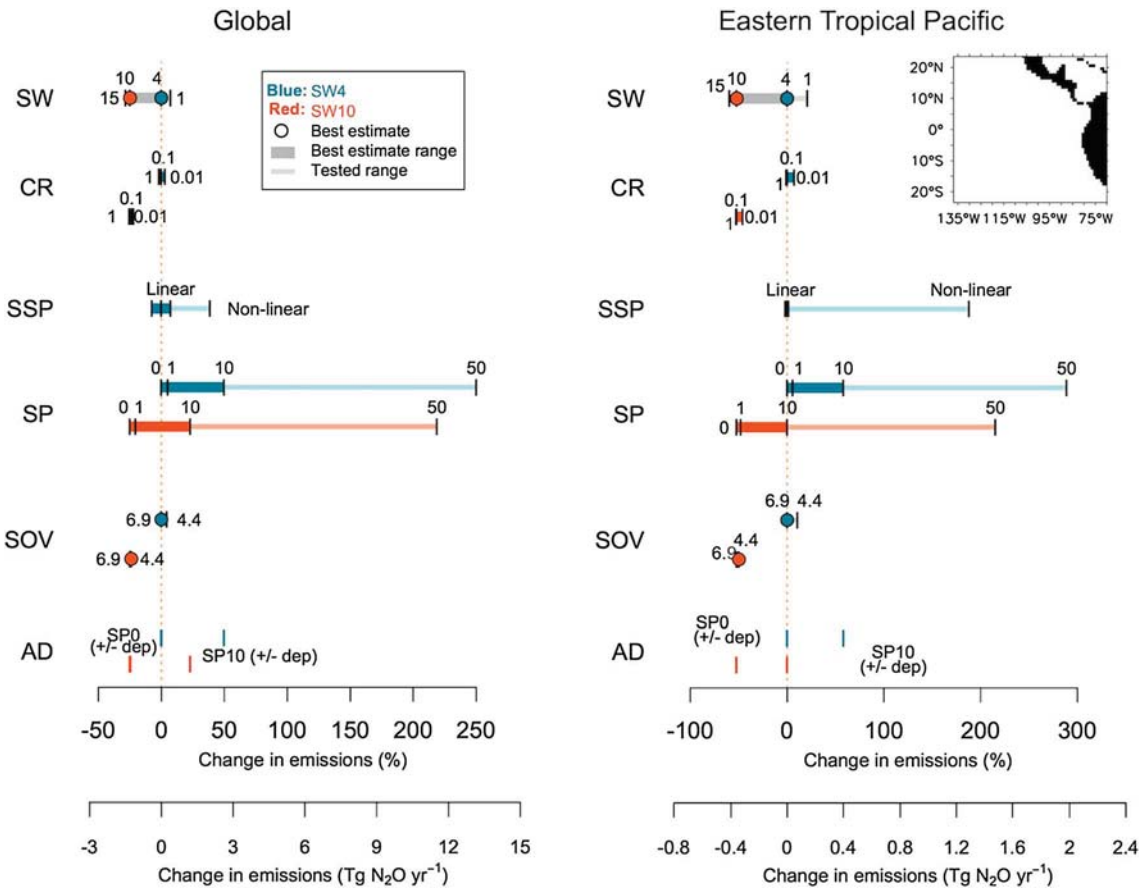

Figure 1. Relative to the baseline scenario (dotted line), here we show the sensitivity of modeled N_2O emissions in the ETP[a] to changes in model parameters[b]. [a]ETP region defined as Pacific regions between 23.5°N–23.5°S and 137:70°W (shown above). [b]See Table 1 for explanation of abbreviations and values tested.

surface N_2O production rates from nitrification have not yet been quantified in field studies, this assumption represents our best guess of actual rates. However, due to the large uncertainties in surface nitrification and its relationship to N_2O, this study cannot quantitatively describe the impact of surface nitrification on marine N_2O emissions. Instead, we seek to merely assess the potential importance of this process.

To compare the sensitivity analyses, one combination of parameters, labeled as the "baseline scenario," was chosen to represent our best guess for N_2O model parameterizations (described in Table 1, with reasoning and documentation for the selection of baseline scenario parameters provided in the Supplement). From the baseline scenario, we altered six parameters, one or two at a time. In this way, the effect of individual parameter changes on simulated oceanic N_2O emissions were assessed, as well as some of the major interactions between parameters. Individual uncertainties derived from sensitivity analyses were then added together to produce one total uncertainty range relative to the baseline scenario that pertains to the parameters tested.

The six parameters tested are not comprehensive of all potential parameters which might affect N_2O emissions; for example, we assumed that the impacts of temperature and depth on subsurface N_2O production were negligible [*Zamora et al.*, 2012], and the surface mediation of fluxes from surfactants [*Kock et al.*, 2012] had no effect. Although the effect of air-sea gas exchange parameterization should not have large effects on the relative importance of the various uncertainties tested here, it could affect total emissions to the atmosphere.

3. Results and Discussion

Figure 1 summarizes the changes in N_2O emissions (globally and within the ETP) caused by uncertainty in model parameterizations. Based on the UVic model, the greatest uncertainties in global N_2O emissions were caused by nitrification-derived surface production of N_2O (abbreviated as SP). SP is not likely to interact with

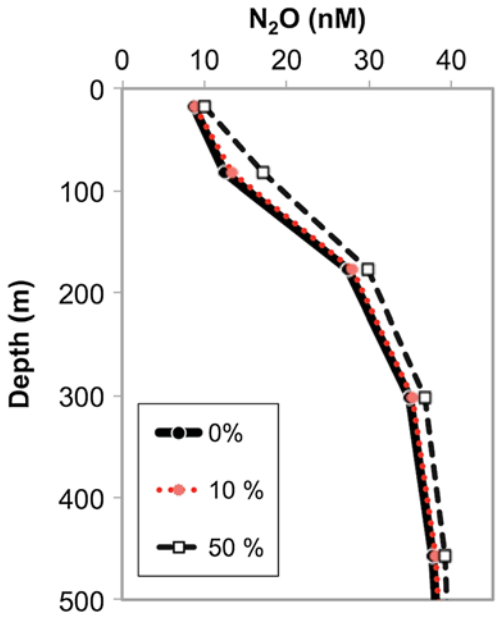

Figure 2. Modeled regional N_2O profiles of the ETP (nM) (defined as region in Figure 1) for the baseline scenario with 0, 10, and 50% surface nitrification. Differences in the upper 100 m are small (<1 and 5 nM for surface nitrification of 10 and 50%, respectively).

most other parameters that are primarily sensitive to O_2 concentrations (e.g., subsurface N_2O production (SSP), the N_2O consumption rate at low O_2 (CR), suboxic volume (SOV), and the unknown oxygen concentration at which net N_2O production switches to net N_2O consumption (SW)). The exception was the potential impact of atmospheric inorganic nitrogen deposition (AD) on N_2O emissions, as AD may spur surface water production of N_2O. However, the interactions between SP and AD were tested and found to be negligible (Figure 1), in good agreement with previous work finding that AD is not a major contributor to global N_2O emissions [*Suntharalingam et al.*, 2012].

SW was the second largest uncertainty in global N_2O emissions. Unlike with SP, the SW might have an effect on the simulated importance of other subsurface parameters, because it affects the volume of O_2 that is relevant for the other parameterizations. Therefore, we simulated the change in N_2O emissions for all other parameters at the two SW values considered as the best estimates (i.e., 4 and 10 μM O_2). The exception is SSP because the study upon which the severely nonlinear parameterization is based precludes a SW of 10 μM [*Goreau et al.*, 1980; *Suntharalingam et al.*, 2000]. However, marine global N_2O emissions were relatively insensitive to most of the other parameters tested, independent of SW value (Figure 1). The other parameterizations, including the effect of reduced SOV had minor (<15%) impacts on N_2O emissions globally and within the ETP.

We found that the ETP had higher relative uncertainties in N_2O emissions than globally because of the regional importance of oxygen minimum zones and the high-surface water productivity (both factors related to the most important uncertainties in N_2O production). SP contributed a large portion of the total uncertainty in the ETP, along with the SW. Within the ETP alone, there also appeared to be relatively high uncertainty caused by assuming a severely nonlinear SSP parameterization (Figure 1). Note however that the nonlinear SSP parameterization [*Suntharalingam et al.*, 2000] is not likely to be realistic for the ETP, because this parameterization had a poor fit to the regional data [*Zamora et al.*, 2012]. We show the effect of the widely referred to SSP severely nonlinear parameterization only to indicate that while it had a relatively minor net impact on global emissions, it could have important consequences on modeled emissions in the ETP, leading to unrealistically large regional N_2O emissions in our model. Uncertainties in the linear SSP parameterization itself were small, altering ETP N_2O flux by ~7% (Figure 1).

While the largest uncertainties in global N_2O emissions come from SP, it is unfortunately very difficult to verify the amount of N_2O actually produced in the upper 100 m. One study indicates that up to 18–33% of surface water NH_4^+ is nitrified [*Yool et al.*, 2007]. Our model indicated that even low-surface nitrification levels (10% of surface water NH_4^+) can increase N_2O emissions to the atmosphere by 50%, assuming similar N_2O production from nitrification as in the subsurface. However, N_2O production in the upper 100 m from 10% nitrification levels would be very difficult to actually observe. First, rapid air-sea gas exchange could mask even large N_2O sources [*Ward*, 2011]. In Figure 2, we show that modeled ETP surface water N_2O profiles in the upper 100 m at 10% nitrification would produce less than a 1 nM difference in N_2O concentrations compared to a simulation without any N_2O production in the euphotic zone—a difference that is barely, if at all, measurable (note that the signal from SP would be higher in the ETP than globally due to the high regional primary production). Second, fast rates of phytoplankton NH_4^+ assimilation prevent an accumulation of surface water NH_4^+ and an accurate measurement of nitrification [*Ward*, 2011]. Finally, it is difficult to distinguish upwelling-driven N_2O emissions from SP-derived N_2O emissions caused by upwelling-driven production. Although we have not tested different air-sea gas parameterizations in this work, air-sea gas exchange parameterization should not affect

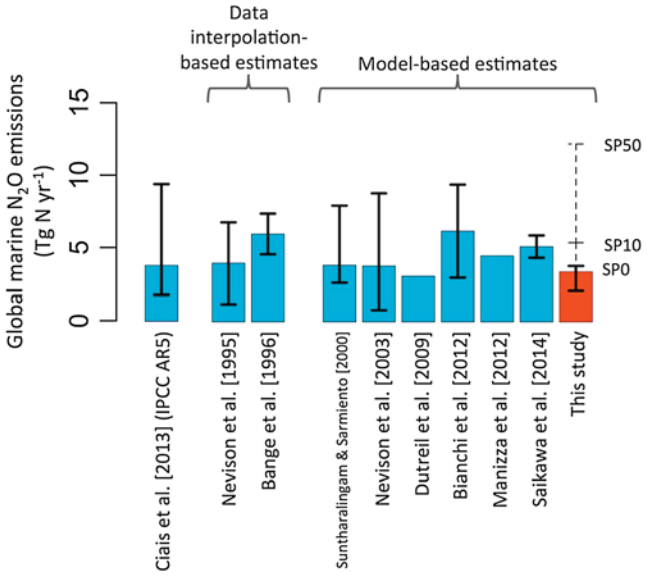

Figure 3. Estimates of global marine N_2O emissions from the ocean to the atmosphere, based on data-interpolation methods and models. Uncertainty ranges due to various SP parameterizations are shown for our model.

the source/sink terms explored here. However, it could affect N_2O gradients and thus should be addressed in future assessments of the magnitude of SP.

Adding a SP scenario generally caused a <1 nM difference in N_2O profiles. However, global surface emissions between the scenarios were more distinctively variable, ranging from 3.4 to 11.7 Tg N yr^{-1} in the SP0 and SP50 scenarios, respectively (Figure 3). Comparing with data interpolation-based N_2O flux estimates (Figure 3), we find that a SP of 50% provides unrealistically high marine N_2O emissions, whereas a SP of ≤10% could be reasonable.

4. Conclusions

We assessed six of the major uncertainties in the marine N_2O emissions using an Earth system climate model with a focus on the eastern tropical Pacific. By far, the largest uncertainty is the potential for surface N_2O production from nitrification, which accounts for huge potential ranges in marine N_2O emissions. Because it is difficult to assess the likelihood of N_2O production from surface nitrification based on chemical assessments alone, there might be much larger marine N_2O emissions to the atmosphere than previously assumed.

The next most significant uncertainty in N_2O emissions was the O_2 concentration at which net N_2O production switches to net N_2O consumption. The range of values considered possible here (1–15 μM O_2) caused an 81% change in ETP N_2O emissions. Because it becomes increasingly difficult to accurately assess the differences between observations and models at low O_2 concentrations (especially at ≤1–4 μM O_2), our findings quantitatively support previous work, suggesting that accurate determination of suboxic volume is vital to determining N_2O emissions [e.g., *Codispoti*, 2010].

Oceanic N_2O emissions are an important source of N_2O to the atmosphere. If surface nitrification does not occur, our study suggests a large reduction in the uncertainty range in previous ocean emissions: from ~7.6 Tg N yr^{-1} [*Ciais et al.*, 2013] to 1.6 Tg N yr^{-1}. This reduction in uncertainty is based on a more thorough testing of literature values for N_2O marine emission uncertainties. However, assuming that 10% of surface remineralized N is nitrified and that similar amounts of N_2O produced in the surface as in the subsurface from nitrification, the uncertainty range in marine N_2O emissions goes back up to 3.3 Tg N yr^{-1}.

Surface nitrification-derived N_2O production (SP) is a possible pathway of N_2O into the atmosphere. As this pathway is yet unverified but even small amounts could account for large N_2O emissions, the potential for SP should be studied in further detail, particularly because SP might be susceptible to global changes in primary production and acidification [*Dore et al.*, 1998; *Law*, 2008; *Beman et al.*, 2012]. To constrain these estimates, more investigations on the emissions of marine N_2O to the atmosphere are needed, as are biological studies assessing the potential for N_2O emissions from surface waters.

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