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**Oceanic N<sub>2</sub>O emissions in the 21st century**

J. Martinez-Rey et al.

# Oceanic N<sub>2</sub>O emissions in the 21st century

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

The ocean is a substantial source of nitrous oxide ( $\text{N}_2\text{O}$ ) to the atmosphere, but little is known on how this flux might change in the future. Here, we investigate the potential evolution of marine  $\text{N}_2\text{O}$  emissions in the 21st century in response to anthropogenic climate change using the global ocean biogeochemical model NEMO-PISCES. We implemented two different parameterizations of  $\text{N}_2\text{O}$  production, which differ primarily at low oxygen ( $\text{O}_2$ ) conditions. When forced with output from a climate model simulation run under the business-as-usual high  $\text{CO}_2$  concentration scenario (RCP8.5), our simulations suggest a decrease of 4 to 12% in  $\text{N}_2\text{O}$  emissions from 2005 to 2100, i.e., a reduction from 4.03/3.71 to 3.54/3.56  $\text{Tg N yr}^{-1}$  depending on the parameterization. The emissions decrease strongly in the western basins of the Pacific and Atlantic oceans, while they tend to increase above the Oxygen Minimum Zones (OMZs), i.e., in the Eastern Tropical Pacific and in the northern Indian Ocean. The reduction in  $\text{N}_2\text{O}$  emissions is caused on the one hand by weakened nitrification as a consequence of reduced primary and export production, and on the other hand by stronger vertical stratification, which reduces the transport of  $\text{N}_2\text{O}$  from the ocean interior to the ocean surface. The higher emissions over the OMZ are linked to an expansion of these zones under global warming, which leads to increased  $\text{N}_2\text{O}$  production associated primarily with denitrification. From the perspective of a global climate system, the averaged feedback strength associated with the projected decrease in oceanic  $\text{N}_2\text{O}$  emissions amounts to around  $-0.009 \text{ W m}^{-2} \text{ K}^{-1}$ , which is comparable to the potential increase from terrestrial  $\text{N}_2\text{O}$  sources. However, the assesment for a compensation between the terrestrial and marine feedbacks calls for an improved representation of  $\text{N}_2\text{O}$  production terms in fully coupled next generation of Earth System Models.

## Oceanic $\text{N}_2\text{O}$ emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 1 Introduction

Nitrous oxide ( $\text{N}_2\text{O}$ ) is a gaseous compound responsible for two key feedback mechanisms within the Earth's climate. First, it acts as a long-lived and powerful greenhouse gas (Prather et al., 2012) ranking third in anthropogenic radiative forcing after carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ) (Myrhe et al., 2013). Secondly, the ozone ( $\text{O}_3$ ) layer depletion in the future might be driven mostly by  $\text{N}_2\text{O}$  after the drastic reductions in CFCs emissions start to show their effect on stratospheric chlorine levels (Ravishankara et al., 2009). The atmospheric concentration of  $\text{N}_2\text{O}$  is determined by the natural balance between sources from land and ocean and the destruction of  $\text{N}_2\text{O}$  in the atmosphere largely by reaction with OH radicals (Crutzen, 1970; Johnston, 1971). The natural sources from land and ocean amount to  $\sim 6.6$  and  $3.8 \text{ Tg N yr}^{-1}$ , respectively (Ciais et al., 2013). Anthropogenic activities currently add an additional  $6.7 \text{ Tg N yr}^{-1}$  to the atmosphere that caused atmospheric  $\text{N}_2\text{O}$  to increase by 18 % since pre-industrial times (Ciais et al., 2013), reaching 325 ppb in the year 2012 (NOAA ESRL Global Monitoring Division, Boulder, Colorado, USA, <http://esrl.noaa.gov/gmd/>).

Using a compilation of 60 000 surface ocean observations of the partial pressure of  $\text{N}_2\text{O}$  ( $p\text{N}_2\text{O}$ ), Nevison et al. (1995) computed a global ocean source of  $4 \text{ Tg N yr}^{-1}$ , with a large range of uncertainty from 1.2 to  $6.8 \text{ Tg N yr}^{-1}$ . Model derived estimates also differ widely, i.e., between 1.7 and  $8 \text{ Tg N yr}^{-1}$  (Nevison et al., 2003; Suntharalingam et al., 2000). These large uncertainties are a consequence of too few observations and of poorly known  $\text{N}_2\text{O}$  formation mechanisms, reflecting a general lack of understanding of key elements of the oceanic nitrogen cycle (Gruber and Galloway, 2008; Zehr and Ward, 2002), and of  $\text{N}_2\text{O}$  in particular (e.g., Zamora et al., 2012; Bange et al., 2009; Freig et al., 2012, among others). A limited number of interior ocean  $\text{N}_2\text{O}$  observations were made available only recently (Bange et al., 2009), but they contain large temporal and spatial gaps. Information on the rates of many important processes remains insufficient, particularly in natural settings. There are only few studies from a limited number of specific regions such as the Arabian Sea, Central and North Pacific, the Bedford

**BGD**

11, 16703–16742, 2014

### Oceanic $\text{N}_2\text{O}$ emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Basin and the Scheldt estuary, which can be used to derive and test model parameterizations (Mantoura et al., 1993; Bange et al., 2000; Elkins et al., 1978; Yoshida et al., 1989; Punshon and Moore, 2004; De Wilde and De Bie, 2000).

$N_2O$  is formed in the ocean interior through two major pathways and consumed only in oxygen minimum zones through denitrification (Zamora et al., 2012). The first production pathway is associated with nitrification (conversion of ammonia,  $NH_4^+$ , into nitrate,  $NO_3^-$ ), and occurs when dissolved  $O_2$  concentrations are above  $20 \mu mol L^{-1}$ . We subsequently refer to this pathway as the high- $O_2$  pathway. The second production pathway is associated with a series of processes when  $O_2$  concentrations fall below  $\sim 5 \mu mol L^{-1}$  and involve a combination of nitrification and denitrification (hereinafter referred to as low- $O_2$  pathway) (Cohen and Gordon, 1978; Goreau et al., 1980; Elkins et al., 1978). As nitrification is one of the processes involved in the aerobic remineralization of organic matter, it occurs nearly everywhere in the global ocean with a global rate at least one order of magnitude larger than the global rate of water column denitrification (Gruber, 2008). A main reason is that denitrification in the water column is limited to the OMZs, which occupy only a few percent of the total ocean volume (Bianchi et al., 2012). This is also the only place in the water column where  $N_2O$  is being consumed.

The two production pathways have very different  $N_2O$  yields, i.e., fractions of nitrogen-bearing products that are transformed to  $N_2O$ . For the high- $O_2$  pathway, the yield is typically rather low, i.e., only about 1 in several hundred molecules of ammonium escapes as  $N_2O$  (Cohen and Gordon, 1979). In contrast, in the low- $O_2$  pathway, and particularly during denitrification, this fraction may go up to as high as 1 : 1, i.e., that all nitrate is turned into  $N_2O$  (Tiedje, 1988). The relative contribution of the two pathways to global  $N_2O$  production is not well established. Sarmiento and Gruber (2006) suggested that the two may be of equal importance, but more recent estimates suggest that the high- $O_2$  production pathway dominates global oceanic  $N_2O$  production (Freing et al., 2012).

Two strategies have been pursued in the development of parameterizations for  $N_2O$  production in global biogeochemical models. The first approach builds on the impor-

**BGD**

11, 16703–16742, 2014

## Oceanic $N_2O$ emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tance of the nitrification pathway and its close association with the aerobic remineralization of organic matter. As a result the production of N<sub>2</sub>O and the consumption of O<sub>2</sub> are closely tied to each other, leading to a strong correlation between the concentration of N<sub>2</sub>O and the apparent oxygen utilization (AOU). This has led to the development of two sets of parameterizations, one based on concentrations, i.e., directly as a function of AOU (Butler et al., 1989) and the other based on the rate of oxygen utilization, i.e. OUR (Freing et al., 2009). Additional variables have been introduced to allow for differences in the yield, i.e., the ratio of N<sub>2</sub>O produced over oxygen consumed, such as temperature (Butler et al., 1989) or depth (Freing et al., 2009). In the second approach, the formation of N<sub>2</sub>O is modeled more mechanistically, and tied to both nitrification and denitrification by an O<sub>2</sub> dependent yield (Suntharalingam and Sarmiento, 2000; Nevison et al., 2003; Jin and Gruber, 2003). Since most models do not include nitrification explicitly, the formation rate is actually coupled directly to the remineralization of organic matter. Regardless of the employed strategy, all parameterizations depend to first order on the amount of organic matter that is being remineralized in the ocean interior, which is governed by the export of organic carbon to depth. The dependence of N<sub>2</sub>O production on oxygen levels and on other parameters such as temperature only acts at second order. This has important implications not only for the modeling of the present-day distribution of N<sub>2</sub>O in the ocean, but also for the sensitivity of marine N<sub>2</sub>O to future climate change.

Over this century, climate change will perturb marine N<sub>2</sub>O formation in multiple ways. Changes in productivity will drive changes in the export of organic matter to the ocean interior (Steinacher et al., 2010; Bopp et al., 2013) and hence affect the level of marine nitrification. Ocean warming might increase the rate of N<sub>2</sub>O production during nitrification. Changes in carbonate chemistry (Bindoff et al., 2007) might cause changes in the C : N ratio of the exported organic matter (Riebesell et al., 2007), altering not only the rates of nitrification, but also the ocean interior oxygen levels (Gehlen et al., 2011). Finally, the expected general loss of oxygen (Keeling et al., 2010; Cocco et al., 2012; Bopp et al., 2013) could substantially affect denitrification and the N<sub>2</sub>O production.

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**Oceanic N<sub>2</sub>O  
emissions in the 21st  
century**J. Martinez-Rey et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Models used for IPCC's 4th assessment report estimated a decrease between 2 and 13 % in primary production (PP) under the business-as-usual high CO<sub>2</sub> concentration scenario A2 (Steinacher et al., 2010). A more recent multi-model analysis based on the models used in IPCC's 5th assessment report also suggest a large reduction of PP down to 18 % by 2100 for the RCP8.5 scenario (Bopp et al., 2013). In these simulations, the export of organic matter is projected to decrease between 6 and 18 % in 2100 (Bopp et al., 2013), with a spatially distinct pattern: in general, productivity and export are projected to decrease at mid- to low-latitudes in all basins, while productivity and export are projected to increase in the high-latitudes and in the South Pacific subtropical gyre (Bopp et al., 2013). A wider spectrum of responses was reported regarding changes in the ocean oxygen content. While all models simulate decreased oxygen concentrations in response to anthropogenic climate change (by about 2 to 4 % in 2100), and particularly in the mid-latitude thermocline regions, no agreement exists with regard to the hypoxic regions, i.e., those having oxygen levels below 60 μmol L<sup>-1</sup> (Cocco et al., 2012; Bopp et al., 2013). Some models project these regions to expand, while others project a contraction. Even more divergence in the results exists for the suboxic regions, i.e., those having O<sub>2</sub> concentrations below 5 μmol L<sup>-1</sup> (Keeling et al., 2010; Deutsch et al., 2011; Cocco et al., 2012; Bopp et al., 2013), although the trend for most models is pointing towards an expansion. At the same time, practically none of the models is able to correctly simulate the current distribution of oxygen in the OMZ (Bopp et al., 2013). In summary, while it is clear that major changes in ocean biogeochemistry are looming ahead (Gruber, 2011), with substantial impacts on the production and emission of N<sub>2</sub>O, our ability to project these changes with confidence is limited.

In this study, we explore the implications of these future changes in ocean physics and biogeochemistry on the marine N<sub>2</sub>O cycle, and make projections of the oceanic N<sub>2</sub>O emissions from year 2005 to 2100 under the high CO<sub>2</sub> concentration scenario RCP8.5. We analyze how changes in biogeochemical and physical processes such as net primary production (NPP), export production and vertical stratification in this cen-

5 tury translate into changes in oceanic N<sub>2</sub>O emissions to the atmosphere. To this end, we use the NEMO-PISCES ocean biogeochemical model, which we have augmented with two different N<sub>2</sub>O parameterizations, permitting us to evaluate changes in the marine N<sub>2</sub>O cycle at the process level, especially with regard to production pathways in high and low oxygen regimes. We demonstrate that while future changes in the marine N<sub>2</sub>O cycle will be substantial, the net emissions of N<sub>2</sub>O appear to change relatively little, i.e., they are projected to decrease by about 10 % in 2100.

## 2 Methodology

### 2.1 NEMO-PISCES model

10 Future projections of the changes in the oceanic N<sub>2</sub>O cycle were performed using the PISCES ocean biogeochemical model (Aumont and Bopp, 2006) in offline mode with physical forcings derived from the IPSL-CM5A-LR coupled model (Dufresne et al., 2013). The horizontal resolution of NEMO ocean general circulation model is 2° × 2° cos Ø (Ø being the latitude) with enhanced latitudinal resolution at the equator of 0.5°. PISCES is a biogeochemical model with five nutrients (NO<sub>3</sub>, NH<sub>4</sub>, PO<sub>4</sub>, Si  
15 and Fe), two phytoplankton groups (diatoms and nanophytoplankton), two zooplankton groups (micro and mesozooplankton), and two non-living compartments (particulate and dissolved organic matter). Phytoplankton growth is limited by nutrient availability and light. Constant Redfield C : N : P ratios of 122 : 16 : 1 are assumed (Takahashi et al., 1985), while all other ratios, i.e., those associated with chlorophyll, iron, and silicon (Chl : C, Fe : C and Si : C) vary dynamically.

### 2.2 N<sub>2</sub>O parameterizations in PISCES

25 We implemented two different parameterizations of N<sub>2</sub>O production in NEMO-PISCES. The first one, adapted from Butler et al. (1989) follows the oxygen consumption approach, with a temperature dependent modification of the N<sub>2</sub>O yield (P.TEMP). The

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



second one is based on Jin and Gruber (2003) (P.OMZ), following the more mechanistic approach, i.e., it considers the different processes occurring at differing oxygen concentrations in a more explicit manner.

The P.TEMP parameterization assumes that the N<sub>2</sub>O production is tied to nitrification only with a yield that is at first order constant. This is implemented in the model by tying the N<sub>2</sub>O formation in a linear manner to O<sub>2</sub> consumption. A small temperature dependence is added to the yield to reflect the potential impact of temperature on metabolic rates. The production term of N<sub>2</sub>O, i.e.,  $J^{P.TEMP}(N_2O)$ , is then mathematically formulated as:

$$J^{P.TEMP}(N_2O) = (\gamma + \theta T)J(O_2)_{consumption} \quad (1)$$

where  $\gamma$  is a background yield ( $0.53 \times 10^{-4} \text{ mol N}_2\text{O}(\text{mol O}_2 \text{ consumed})^{-1}$ ),  $\theta$  is the temperature dependency of  $\gamma$  ( $4.6 \times 10^{-6} \text{ mol N}_2\text{O}(\text{mol O}_2)^{-1} \text{ K}^{-1}$ ),  $T$  is temperature (K), and  $J(O_2)_{consumption}$  is the sum of all biological O<sub>2</sub> consumption terms within the model. Although this parameterization is very simple, a recent analysis of N<sub>2</sub>O observations supports such an essentially constant yield, even in the OMZ of the Eastern Tropical Pacific (Zamora et al., 2012).

The P.OMZ parameterization, formulated after Jin and Gruber (2003), assumes that the overall yield consists of a constant background yield and an oxygen dependent yield. The former is presumed to represent the N<sub>2</sub>O production by nitrification, while the latter is presumed to reflect the enhanced production of N<sub>2</sub>O at low oxygen concentrations, in part driven by denitrification, but possibly including nitrification as well. This parameterization includes the consumption of N<sub>2</sub>O in suboxic conditions. This gives:

$$J^{P.OMZ}(N_2O) = (\alpha + \beta f(O_2))J(O_2)_{consumption} - kN_2O \quad (2)$$

where  $\alpha$  is, as in Eq. (1), a background yield ( $0.9 \times 10^{-4} \text{ mol N}_2\text{O}(\text{mol O}_2 \text{ consumed})^{-1}$ ),  $\beta$  is a yield parameter that scales the oxygen dependent function ( $6.2 \times 10^{-4}$ ),  $f(O_2)$

**Oceanic N<sub>2</sub>O emissions in the 21st century**

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



is a unitless oxygen-dependent step-like modulating function, as suggested by laboratory experiments (Goreau et al., 1980) (Fig. S1, Supplement), and  $k$  is the 1st order rate constant of  $N_2O$  consumption close to anoxia (zero otherwise). For  $k$ , we have adopted a value of  $0.138 \text{ yr}^{-1}$  following Bianchi et al. (2012) while we set the consumption regime for  $O_2$  concentrations below  $5 \mu\text{mol L}^{-1}$ .

The P.OMZ parameterization permits us to separately identify the  $N_2O$  formation pathways associated with nitrification and those associated with low-oxygen concentrations (nitrification/denitrification). Specifically, we consider the source term  $\alpha J(O_2)_{\text{consumption}}$  as that associated with the nitrification pathway, while we associated the source term  $\beta f(O_2)J(O_2)_{\text{consumption}}$  with the low-oxygen processes (Fig. S2, Supplement).

We employ a standard bulk approach for simulating the loss of  $N_2O$  to the atmosphere via gas exchange. We use the formulation of Wanninkhof et al. (1992) for estimating the gas transfer velocity, adjusting the Schmidt number for  $N_2O$  and using the solubility constants of  $N_2O$  given by Weiss and Price (1980). We assume a constant atmospheric  $N_2O$  concentration of 284 ppb in all simulations.

### 2.3 Experimental design

NEMO-PISCES was first spun up during 3000 years using constant pre-industrial dynamical forcings fields from IPSL-CM5A-LR (Dufresne et al., 2013) without activating the  $N_2O$  parameterizations. This spin-up phase was followed by a 150 yr long simulation, forced by the same dynamical fields now with  $N_2O$  production and  $N_2O$  sea-to-air flux embedded. The  $N_2O$  concentration at all grid points was prescribed initially to  $20 \text{ nmol L}^{-1}$ , which is consistent with the MEMENTO database average value of  $18 \text{ nmol L}^{-1}$  below 1500 m (Bange et al., 2009). During the 150 yr spin-up, we diagnosed the total  $N_2O$  production and  $N_2O$  sea-to-air flux and adjusted the  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\theta$  parameters in order to achieve a total  $N_2O$  sea-to-air flux in the two parameterizations at equilibrium close to  $3.85 \text{ Tg N yr}^{-1}$  (Ciais et al., 2013). In addition, the relative con-

**BGD**

11, 16703–16742, 2014

## Oceanic $N_2O$ emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tribution of the high-O<sub>2</sub> pathway in the P.OMZ parameterization was set to 75 % of the total N<sub>2</sub>O production. This assumption is based on growing evidence that nitrification is the dominant pathway of N<sub>2</sub>O production on a global scale, based on estimations considering N<sub>2</sub>O production along with water mass transport (Freing et al., 2012).

5 Projections in NEMO-PISCES of historical (from 1851 to 2005) and future (from 2005 to 2100) simulated periods were done using dynamical forcing fields from IPSL-CM5A-LR. These dynamical forcings were applied in an offline mode, i.e. monthly means of temperature, velocity, wind speed or radiative flux were used to force NEMO-PISCES. Future simulations used the business-as-usual high CO<sub>2</sub> concentration scenario (RCP8.5) until year 2100. Century scale model drifts for all the biogeochemical variables presented, including N<sub>2</sub>O sea-to-air flux, production and inventory, were removed using an additional control simulation with IPSL-CM5A-LR pre-industrial dynamical forcing fields from year 1851 to 2100. Despite the fact that primary production and the export of organic matter to depth were stable in the control simulation, the air–sea N<sub>2</sub>O emissions drifted (an increase of 5 to 12 % in 200 yr depending on the parameterization) due to the short spin-up phase (150 yr) and to the choice of the initial conditions for N<sub>2</sub>O concentrations.

### 3 Present-day oceanic N<sub>2</sub>O

#### 3.1 Contemporary N<sub>2</sub>O fluxes

20 The model simulated air–sea N<sub>2</sub>O emissions show large spatial contrasts, with flux densities varying by one order of magnitude, but with relatively small differences between the two parameterizations (Fig. 1a and b). This is largely caused by our assumption that the dominant contribution (75 %) to the total N<sub>2</sub>O production in the P.OMZ parameterization is the nitrification pathway, which is then not so different from the P.TEMP parameterization, where it is 100 %. As a result, the major part of N<sub>2</sub>O is produced close to the subsurface via nitrification, contributing directly to imprint changes

**BGD**

11, 16703–16742, 2014

## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



into the sea-to-air N<sub>2</sub>O flux without a significant meridional transport (Suntharalingam and Sarmiento, 2000).

Elevated N<sub>2</sub>O emission regions ( $> 50 \text{ mg N m}^{-2} \text{ yr}^{-1}$ ) are found in the Eastern Tropical Pacific, in the northern Indian ocean, in the northwestern Pacific, in the North Atlantic and in the Agulhas Current. In contrast, low fluxes ( $< 10 \text{ mg N m}^{-2} \text{ yr}^{-1}$ ) are simulated in the Atlantic and Pacific subtropical gyres and southern Indian Ocean.

The regions of high N<sub>2</sub>O emissions are in both parameterizations generally consistent with the data product of Nevison et al. (1995) (Fig. 1c), especially in the equatorial latitudes. The largest discrepancies occur in the North Pacific and Southern Ocean. The high N<sub>2</sub>O emissions observed in the North Pacific are not well represented by our model, with a significant shift towards the western part of the Pacific basin, similar to other modeling studies (e.g., Goldstein et al., 2003; Jin and Gruber, 2003). The OMZ, located at approximately 600 m deep in the North Pacific, might be underestimated in our model, which in turn might suppress one potential N<sub>2</sub>O source. Minor discrepancies between model and observations also occur in the Southern Ocean, a region whose role in global N<sub>2</sub>O fluxes remains debated due to the lack of observations and the occurrence of potential artifacts due to interpolation techniques (e.g., Suntharalingam and Sarmiento, 2000; Nevison et al., 2003). In particular, the modeled N<sub>2</sub>O flux maxima peak at around 40° S, i.e., around 10° N to that estimated by Nevison et al. (1995) (Fig. 1d).

### 3.2 Contemporary N<sub>2</sub>O concentrations and the relationship to O<sub>2</sub>

The model results at present day were evaluated against the MEMENTO database (Bange et al., 2009), which contains about 25 000 measurements of co-located N<sub>2</sub>O and dissolved O<sub>2</sub> concentrations. Table 1 summarizes the SD and correlation coefficients for P.TEMP and P.OMZ compared to MEMENTO. The SD of the model output is very similar to MEMENTO, i.e., around  $16 \text{ nmol L}^{-1}$  of N<sub>2</sub>O. However, the correlation coefficients between the sampled data points from MEMENTO and P.TEMP/P.OMZ are 0.49 and 0.42, respectively.



our choice of a too low  $\text{N}_2\text{O}$  consumption rate under essentially anoxic conditions. The  $\text{O}_2$  distribution in the model (Fig. 3c) shows a deficient representation of the OMZs, with higher concentrations than those from observations in the oxygen-corrected World Ocean Atlas (Bianchi et al., 2012). The rest of the  $\text{O}_2$  spectrum is well represented in our model. Finally, it should be considered that most of the MEMENTO data points are from OMZs and therefore  $\text{N}_2\text{O}$  measurements could be biased towards higher values than the actual open ocean average, where our model performs better.

## 4 Future oceanic $\text{N}_2\text{O}$

### 4.1 $\text{N}_2\text{O}$ sea-to-air flux

The global oceanic  $\text{N}_2\text{O}$  emissions decrease relatively little over the next century (Fig. 4a) between 4 and 12%. Namely, in P.TEMP, the emissions decrease by 0.15 from  $3.71 \text{ Tg N yr}^{-1}$  in 1985–2005 to  $3.56 \text{ Tg N yr}^{-1}$  in 2080–2100 and in P.OMZ, the decrease is slightly larger at 12% i.e., amounting to  $0.49 \text{ Tg N yr}^{-1}$  from  $4.03$  to  $3.54 \text{ Tg N yr}^{-1}$ . Notable is also the presence of a negative trend in  $\text{N}_2\text{O}$  emissions over the 20th century, most pronounced in the P.OMZ parameterization. Considering the change over the 20th and 21st centuries together, the decreases increase to 7 and 15%.

These relatively small global decreases mask more substantial changes at the regional scale, with a mosaic of regions experiencing a substantial increase and regions experiencing a substantial decrease (Fig. 4b and c). In both parameterizations, the oceanic  $\text{N}_2\text{O}$  emissions decrease in the northern and south western oceanic basins (e.g., the North Atlantic and Arabian Sea), by up to  $25 \text{ mg N m}^{-2} \text{ yr}^{-1}$ . In contrast, the fluxes are simulated to increase in the Eastern Tropical Pacific and in the Bay of Bengal. For the Benguela Upwelling System (BUS) and the North Atlantic a bi-modal pattern emerges in 2100. As was the case for the present-day distribution of the  $\text{N}_2\text{O}$  fluxes,

**BGD**

11, 16703–16742, 2014

## Oceanic $\text{N}_2\text{O}$ emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the overall similarity between the two parameterizations is a consequence of the dominance of the nitrification (high-O<sub>2</sub>) pathway in both parameterizations.

Nevertheless there are two regions where more substantial differences between the two parameterizations emerge: the region overlying the oceanic OMZ at the BUS and the Southern Ocean. In particular, the P.TEMP parameterization projects a larger enhancement of the flux than P.OMZ at the BUS, whereas the emissions in the Southern Ocean are enhanced in the P.OMZ parameterization.

## 4.2 Drivers of changes in N<sub>2</sub>O emissions

The changes in N<sub>2</sub>O emissions may stem from a change in net N<sub>2</sub>O production, a change in the transport of N<sub>2</sub>O from its location of production to the surface, or any combination of the two, which includes also changes in N<sub>2</sub>O storage. Next we determine the contribution of these mechanisms to the overall decrease in N<sub>2</sub>O emissions that our model simulated for the 21st century.

### 4.2.1 Changes in N<sub>2</sub>O production

In both parameterizations, global N<sub>2</sub>O production is simulated to decrease over the 21st century. The total N<sub>2</sub>O production in P.OMZ decreases by 0.41 TgNyr<sup>-1</sup> in 2080–2100 compared to the mean value over 1985–2005 (Fig. 5a). The parameterization P.OMZ allows to isolate the contributions of high- and low-O<sub>2</sub> and will be analysed in greater detail in the following sections. N<sub>2</sub>O production via the high-O<sub>2</sub> pathway in P.OMZ decreases in the same order than total production, by 0.35 TgNyr<sup>-1</sup> in 2080–2100 compared to present. The N<sub>2</sub>O production in the low-O<sub>2</sub> regions remains almost constant across the experiment. In P.TEMP parameterization, the reduction in N<sub>2</sub>O production is much weaker than in P.OMZ due to the effect of the increasing temperature. N<sub>2</sub>O production decreases by 0.07 TgNyr<sup>-1</sup> in 2080–2100 compared to present (Fig. 5b).

**BGD**

11, 16703–16742, 2014

## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



---

**Oceanic N<sub>2</sub>O  
emissions in the 21st  
century**J. Martinez-Rey et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The vast majority of the changes in the N<sub>2</sub>O production in the P.OMZ parameterization is caused by the high-O<sub>2</sub> pathway with virtually no contribution from the low-O<sub>2</sub> pathway (Fig. 5a). As the N<sub>2</sub>O production in this pathway is solely driven by changes in the O<sub>2</sub> consumption (Eq. 2), which in our model is directly linked to export production, the dominance of this pathway implies that primary driver for the future changes in N<sub>2</sub>O production in our model is the decrease in export of organic matter (CEX). It was simulated to decrease by 0.97 PgCyr<sup>-1</sup> in 2100, and the high degree of correspondence in the temporal evolution of export and N<sub>2</sub>O production in Fig. 5a confirms this conclusion.

The close connection between N<sub>2</sub>O production associated with the high-O<sub>2</sub> pathway and changes in export production is also seen spatially (Fig. 5c), where the spatial pattern of changes in export and changes in N<sub>2</sub>O production are extremely highly correlated (shown by stippling). Most of the small deviations are caused by lateral advection of organic carbon, causing a spatial separation between changes in O<sub>2</sub> consumption and changes in organic matter export.

As there is an almost ubiquitous decrease of export in all of the major oceanic basins except at high latitudes, N<sub>2</sub>O production decreases overall as well. Hotspots of reductions exceeding  $-10 \text{ mgNm}^{-2} \text{ yr}^{-1}$  are found in the North Atlantic, the western Pacific and Indian basins (Fig. 5c). The fewer places where export increases, are also the locations of enhanced N<sub>2</sub>O production. For example, a moderate increase of  $3 \text{ mgNm}^{-2} \text{ yr}^{-1}$  is projected in the Southern Ocean, South Atlantic and Eastern Tropical Pacific. The general pattern of export changes, i.e., decreases in lower latitudes, increase in higher latitudes, is consistent generally with other model projection patterns (Bopp et al., 2013), although there exist very strong model-to-model differences at the more regional scale.

Although the global contribution of the changes in the low-O<sub>2</sub> N<sub>2</sub>O production is small, this is the result of regionally compensating trends. In the model's OMZs, i.e., in the Eastern Tropical Pacific and in the Bay of Bengal, a significant increase in N<sub>2</sub>O production is simulated in these locations (Fig. 5d), with an increase of more than

15 mg N m<sup>-2</sup> yr<sup>-1</sup>. This increase is primarily driven by the expansion of the OMZs in our model (shown by stippling), while changes in export contribute less. In effect, NEMO-PISCES projects a 20 % increase in the hypoxic volume globally, from 10.2 to 12.3 × 10<sup>6</sup> km<sup>3</sup>, and an increase in the suboxic volume from 1.1 to 1.6 × 10<sup>6</sup> km<sup>3</sup> in 2100 (Fig. 5e). Elsewhere, the changes in the N<sub>2</sub>O production through the low-O<sub>2</sub> pathway are dominated by the changes in export, thus following the pattern of the changes seen in the high-O<sub>2</sub> pathway. Overall these changes are negative, and happen to nearly completely compensate the increase in production in the OMZs, resulting in the near constant global N<sub>2</sub>O production by the low-O<sub>2</sub> production pathway up to year 2100.

#### 10 4.2.2 Changes in storage of N<sub>2</sub>O

A steady increase in the N<sub>2</sub>O inventory is observed from present to 2100. The pool of oceanic N<sub>2</sub>O down to 1500 m, i.e., potentially outgassed to the atmosphere, increases by 8.9 Tg N from 1985–2005 to year 2100 in P.OMZ, whereas P.TEMP is less sensitive to changes with an increase of 4.0 Tg N on the time period considered (Fig. 6a).

15 This increase in storage of N<sub>2</sub>O in the ocean interior shows an homogeneous pattern for P.TEMP, with particular hotspots in the North Pacific, North Atlantic and the eastern boundary currents in the Pacific (Fig. 6b). The spatial variability is more pronounced in P.OMZ (Fig. 6c), related in part to the enhanced production associated with OMZs. Most of the projected changes in storage are associated with shoaling of the mixed layer depth (shown by stippling), suggesting that increase in N<sub>2</sub>O inventories is caused by increased ocean stratification. Enhanced ocean stratification, in turn, occurs in response to increasing sea surface temperatures associated with global warming (Sarmiento et al., 2004).

#### 20 4.2.3 Effects of the combined mechanisms on N<sub>2</sub>O emissions

25 The drivers of the future evolution of oceanic N<sub>2</sub>O emissions emerge from the preceding analysis. Firstly, a decrease in the high-O<sub>2</sub> production pathway driven by a reduced

BGD

11, 16703–16742, 2014

## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



organic matter remineralization reduces  $N_2O$  concentrations below the euphotic zone. Secondly, the increased  $N_2O$  inventory at depth is caused by increased stratification and therefore to a less efficient transport to the sea-to-air interface, leading to a less  $N_2O$  flux.

The global changes in  $N_2O$  flux,  $N_2O$  production and  $N_2O$  storage for P.OMZ are presented in Fig. 7. Changes in  $N_2O$  flux and  $N_2O$  production are mostly of the same sign in almost all of the oceanic regions in line with the assumption of nitrification being the dominant contribution to  $N_2O$  production. Changes in  $N_2O$  production close to the subsurface are translated into corresponding changes in  $N_2O$  flux. There is only one oceanic region (Sub-Polar Pacific) where this correlation does not occur.  $N_2O$  inventory increases in all of the oceanic regions. The increase in inventory is particularly pronounced at low latitudes along the eastern boundary currents in the Equatorial and Tropical Pacific. Figure 7 shows how almost all the relevant changes in  $N_2O$  production and storage are related to low-latitude processes, with little or no contribution from changes in polar regions.

The synergy among the driving mechanisms can be explored with a box model pursuing two objectives. First, to reproduce future projections assuming that the only mechanisms ruling the  $N_2O$  dynamics in the future were those that we have proposed in our hypothesis, i.e., increased stratification and reduction of  $N_2O$  production in high- $O_2$  regions. Secondly, to explore a wider range of values for both mixing (i.e., degree of stratification) and efficiency of  $N_2O$  production in high- $O_2$  conditions.

To this end, a box model was designed to explore the response of oceanic  $N_2O$  emissions to changes in export of organic matter (hence  $N_2O$  production only in high- $O_2$  conditions) and changes in the mixing ratio between deep ( $> 100$  m) and surface ( $< 100$  m) layers. We divided the water column into two compartments: a surface layer in the upper 100 m where 80 % of surface  $N_2O$  concentration is outgassed to the atmosphere (Eq. 3), and a deeper layer beyond 100 m, where  $N_2O$  is produced from remineralization as a fraction of the organic matter exported in the ocean interior (Eq. 4). The  $N_2O$  reservoirs in the surface and in the deep layer are allowed to exchange. The

**BGD**

11, 16703–16742, 2014

## Oceanic $N_2O$ emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



exchange is regulated by a mixing coefficient  $\nu$ :

$$\text{surface } \text{N}_2\text{O}; \quad \frac{d\text{N}_2\text{O}^{\text{s}}}{dt} = -\nu \cdot (\text{N}_2\text{O}^{\text{s}} - \text{N}_2\text{O}^{\text{d}}) - \kappa \cdot \text{N}_2\text{O}^{\text{s}} \quad (3)$$

$$\text{deep } \text{N}_2\text{O}; \quad \frac{d\text{N}_2\text{O}^{\text{d}}}{dt} = \nu \cdot (\text{N}_2\text{O}^{\text{s}} - \text{N}_2\text{O}^{\text{d}}) + \varepsilon \cdot \Phi^{\text{POC}} \quad (4)$$

where  $\text{N}_2\text{O}^{\text{s}}$  is  $\text{N}_2\text{O}$  in the surface,  $\text{N}_2\text{O}^{\text{d}}$  is  $\text{N}_2\text{O}$  in the deep reservoir,  $\Phi^{\text{POC}}$  is the flux of POC into the lower compartment,  $\nu$  is the mixing coefficient between both compartments,  $\kappa$  is the fraction of  $\text{N}_2\text{O}^{\text{s}}$  outgassed to the atmosphere and  $\varepsilon$  the fraction of POC leading to  $\text{N}_2\text{O}^{\text{d}}$  formation (Fig. S3 and Table S1, Supplement). Equations (3) and (4) are solved for a combination of POC fluxes and mixing coefficients, reflecting the increasing stratification and the decrease in export production projected by year 2100 (Sarmiento et al., 2004; Bopp et al., 2013).

A decrease in the  $\text{N}_2\text{O}$  flux is observed for a wide range of boundary conditions simulating reduced mixing and export of POC (Fig. 8a). The equivalent of the transient NEMO-PISCES simulation, i.e., a  $-10\%$  decrease in  $\text{N}_2\text{O}$  flux, is achieved for a  $-8\%$  decrease in export in the box model. The most extreme scenario explored with the box model suggests a  $-20\%$  decrease in  $\text{N}_2\text{O}$  flux, although these associated values of mixing and export are clearly unrealistic, from a nearly total stagnation of ocean circulation between the deep and surface layers to an attenuation of export of  $-20\%$  in the global ocean.

The projected increase in  $\text{N}_2\text{O}$  storage in the deep reservoir is reproduced by the box model (Fig. 8b) at a wide range of changes particularly in mixing. Changes in mixing dominate over changes in export as drivers of the increase in the  $\text{N}_2\text{O}$  reservoir at depth. A  $25\%$  decrease in mixing leads to an increase in storage similar to the one projected with NEMO-PISCES ( $+10\%$ ), independently of changes in export of organic matter.

In general, the interplay between mixing and export of organic matter operates differently when  $\text{N}_2\text{O}$  flux or  $\text{N}_2\text{O}$  inventory are considered. The box model experiment

## Oceanic $\text{N}_2\text{O}$ emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



suggests that the evolution of the N<sub>2</sub>O reservoir is driven almost entirely by changes in mixing, while changes of mixing and export of organic matter have similar relevance when modulating N<sub>2</sub>O emissions.

## 5 Caveats in estimating N<sub>2</sub>O using ocean biogeochemical models

5 The use of O<sub>2</sub> consumption as a proxy for the actual N<sub>2</sub>O production expand the uncertainties in N<sub>2</sub>O model estimations. Future model development should aim at the implementation of mechanistic parameterizations of N<sub>2</sub>O production based on nitrification and denitrification rates. Further, in order to determine accurate O<sub>2</sub> boundaries for both N<sub>2</sub>O production and N<sub>2</sub>O consumption at the core of OMZs additional measurements and microbial experiments are needed. The contribution of the high-O<sub>2</sub> pathway that was considered in this model analysis might be a conservative estimate. Freing et al. (2012) suggested that the high-O<sub>2</sub> pathway could be responsible of 93% of the total N<sub>2</sub>O production. Assuming that changes in the N<sub>2</sub>O flux are mostly driven by N<sub>2</sub>O production via nitrification, that would suggest a larger reduction in the marine N<sub>2</sub>O emissions in the future. Moreover, Zamora et al. (2012) observed a higher than expected N<sub>2</sub>O consumption at the core of the OMZ in the Eastern Tropical Pacific, occurring at an upper threshold of 10 μmol L<sup>-1</sup>. The contribution of OMZs to total N<sub>2</sub>O production remains an open question. N<sub>2</sub>O formation associated with OMZs might be counterbalanced by its own local consumption, leading to the attenuation of the only increasing source of N<sub>2</sub>O attributable to the projected future expansion of OMZs (Steinacher et al., 2010; Bopp et al., 2013). Finally, the accurate representation of subsurface O<sub>2</sub> concentration remains as a major challenge for ocean biogeochemical models, as shown by Bopp et al. (2013).

25 The combined effect of climate change and ocean acidification has not been analyzed in this study. N<sub>2</sub>O production processes might be altered by the response of nitrification to increasing levels of seawater pCO<sub>2</sub> (Huesemann et al., 2002; Beman et al., 2011). Beman et al. (2011) reported a reduction in nitrification in response to

### Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



decreasing pH. This result suggests that N<sub>2</sub>O production might decrease beyond what we have estimated only due to climate change. Conversely, negative changes in the ballast effect could potentially reinforce nitrification at shallow depth in response to less efficient POC export to depth and shallow remineralization (Gehlen et al., 2011). Regarding N<sub>2</sub>O formation via denitrification, changes in seawater pH as a consequence of higher levels of CO<sub>2</sub> might not be substantial enough to change the N<sub>2</sub>O production efficiency, assuming a similar response of marine denitrifiers as reported for denitrifying bacteria have in terrestrial systems (Liu et al., 2010). Finally, the C : N ratio in export production (Riebesell et al., 2007) might increase in response to ocean acidification, potentially leading to a greater expansion of OMZs than simulated here (Oschlies et al., 2008; Tagliabue et al., 2011), and therefore to enhanced N<sub>2</sub>O production associated with the low-O<sub>2</sub> pathway.

Changes in atmospheric nitrogen deposition have not been considered in this study. It has been suggested that due to anthropogenic activities the additional amount of reactive nitrogen in the ocean could fuel primary productivity and N<sub>2</sub>O production. Estimates are however low, around 3–4 % of the total oceanic emissions (Suntharalingam et al., 2012).

Longer simulation periods could reveal additional effects on N<sub>2</sub>O transport beyond changes in upwelling or meridional transport of N<sub>2</sub>O close to the subsurface (Suntharalingam and Sarmiento, 2000). Eventual ventilation of the N<sub>2</sub>O reservoir at high latitudes could shed light into the role of upwelling regions as an important source of N<sub>2</sub>O. Additional studies using other ocean biogeochemical models might also yield alternative values using the same parameterizations. N<sub>2</sub>O production is particularly sensitive to the distribution and magnitude of export of organic matter and O<sub>2</sub> fields defined in models.

## BGD

11, 16703–16742, 2014

### Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 6 Contribution of future N<sub>2</sub>O to climate feedbacks

Changes in the oceanic emissions of N<sub>2</sub>O to the atmosphere will have an impact on atmospheric radiative forcing, with potential feedbacks on the climate system. Based on the estimated 4 to 12 % decrease in N<sub>2</sub>O sea-to-air flux over the 21st century under RCP8.5, we estimated the feedback factor for these changes as defined by Xu-Ri et al. (2012). Considering the reference value of the pre-industrial atmospheric N<sub>2</sub>O concentration of 280 ppb in equilibrium, and its associated global N<sub>2</sub>O emissions of 11.8 Tg Nyr<sup>-1</sup>, we quantify the resulting changes in N<sub>2</sub>O concentration per degree for the two projected emissions in 2100 using P.TEMP and P.OMZ. The model projects changes in N<sub>2</sub>O emissions of -0.16 and -0.48 Tg Nyr<sup>-1</sup> respectively, whereas surface temperature is assumed to increase globally by 3 °C on average according to the physical forcing used in our simulations. These results yield -0.05 and -0.16 Tg Nyr<sup>-1</sup> K<sup>-1</sup>, or alternatively -1.25 and -3.8 ppb K<sup>-1</sup> for P.TEMP and P.OMZ respectively. Using Joos et al. (2001) we calculate the feedback factor in equilibrium for projected changes in emissions to be -0.005 and -0.014 W m<sup>-2</sup> K<sup>-1</sup> in P.TEMP and P.OMZ.

Stocker et al. (2013) projected changes in terrestrial N<sub>2</sub>O emissions in 2100 using transient model simulations leading to feedback strengths between +0.001 and +0.015 W m<sup>-2</sup> K<sup>-1</sup>. Feedback strengths associated with the projected decrease of oceanic N<sub>2</sub>O emissions are of the same order of magnitude as those attributable to changes in the terrestrial sources of N<sub>2</sub>O, yet opposite in sign, suggesting a compensation of changes in radiative forcing due to future increasing terrestrial N<sub>2</sub>O emissions. At this stage, potential compensation between land and ocean emissions is to be taken with caution, as it relies of a single model run with constant atmospheric N<sub>2</sub>O.

## 7 Conclusions

Our simulations suggest that anthropogenic climate change could lead to a global decrease in oceanic N<sub>2</sub>O emissions during the 21st century. This maximum projected de-

**BGD**

11, 16703–16742, 2014

### Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



crease of 12 % in marine N<sub>2</sub>O emissions for the business-as-usual high CO<sub>2</sub> emissions scenario would compensate for the estimated increase in N<sub>2</sub>O fluxes from the terrestrial biosphere in response to anthropogenic climate change (Stocker et al., 2013), so that the climate–N<sub>2</sub>O feedback may be more or less neutral over the coming decades.

5 The main mechanisms contributing to the reduction of marine N<sub>2</sub>O emissions are a decrease in N<sub>2</sub>O production in high oxygenated waters as well as an increase in ocean vertical stratification that acts to decrease the transport of N<sub>2</sub>O from the sub-surface to the surface ocean. Despite the decrease in both N<sub>2</sub>O production and N<sub>2</sub>O emissions, simulations suggest that the global marine N<sub>2</sub>O inventory may increase  
10 from 2005 to 2100. This increase is explained by the reduced transport of N<sub>2</sub>O from the production zones to the air–sea interface.

Differences between the two parameterizations used here are modest, and the role of warming in P.TEMP or higher N<sub>2</sub>O yields at low-O<sub>2</sub> concentrations in P.OMZ does not translate into significant differences in our model projections. The dominant high-  
15 O<sub>2</sub> N<sub>2</sub>O production pathway drives not only the general decrease in N<sub>2</sub>O emissions but also the homogeneousness between the two parameterizations considered.

The N<sub>2</sub>O production pathways demand however a better understanding in order to enable an improved representation of processes in models. At a first order, the efficiencies of the production processes in response to higher temperatures or increased  
20 seawater pCO<sub>2</sub> are required. Second order effects such as changes in the O<sub>2</sub> boundaries at which nitrification and denitrification occur must be also taken into account. In the absence of process-based parameterizations, N<sub>2</sub>O production parameterizations will still rely on export of organic carbon and oxygen levels. Both need to be improved  
25 in global biogeochemical models.

The same combination of mechanisms (i.e., change in export production and ocean stratification) have been identified as drivers of changes in oceanic N<sub>2</sub>O emissions during the Younger Dryas by Goldstein et al. (2003). The N<sub>2</sub>O flux decreased, while the N<sub>2</sub>O reservoir was fueled by longer residence times of N<sub>2</sub>O caused by increased

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## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

stratification. Whether these mechanisms are plausible drivers of changes beyond year 2100 remains an open question that needs to be addressed with longer simulations.

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## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## BGD

11, 16703–16742, 2014

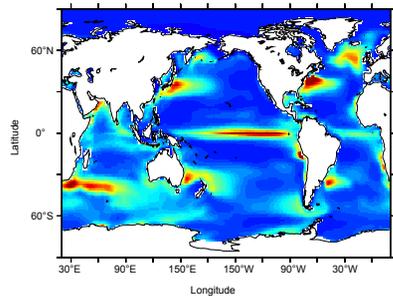
## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

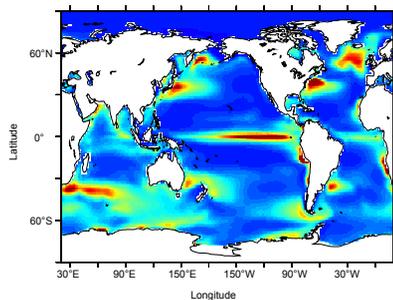
[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Table 1.** SD and correlation coefficients between P.TEMP and P.OMZ parameterizations with respect to MEMENTO database observations (Bange et al., 2009).

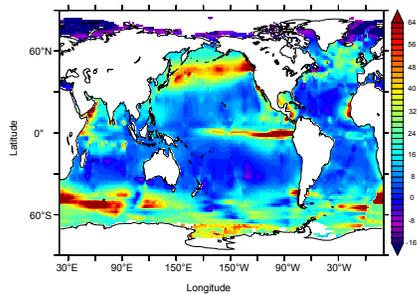
	P.TEMP	P.OMZ	OBS
SD (in nmolN <sub>2</sub> OL <sup>-1</sup> )	12	18	16
Correlation coefficient with obs.	0.49	0.42	–



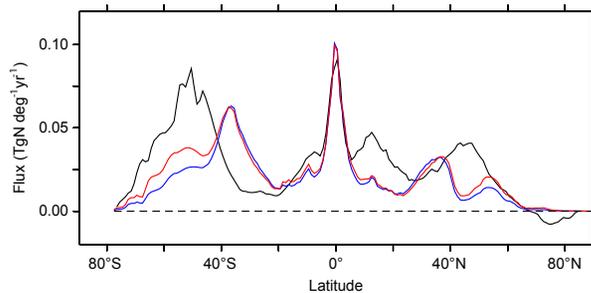
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# BGD

11, 16703–16742, 2014

## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**Figure 1.** N<sub>2</sub>O sea-to-air flux (in mgN m<sup>-2</sup> yr<sup>-1</sup>) from **(a)** P.TEMP parameterization averaged for the 1985 to 2005 time period in the historical simulation, **(b)** P.OMZ parameterization over the same time period, **(c)** data product of Nevison et al. (1995) and **(d)** latitudinal N<sub>2</sub>O sea-to-air flux (in TgN deg<sup>-1</sup> yr<sup>-1</sup>) from Nevison et al. (1995) (black), P.TEMP (blue) and P.OMZ (red).

## BGD

11, 16703–16742, 2014

### Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

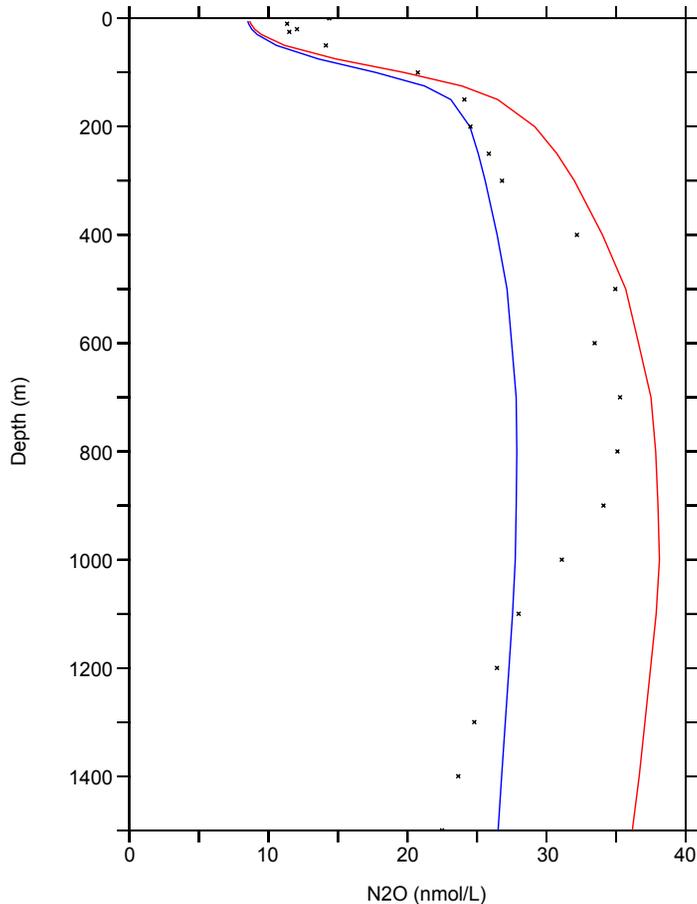
[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)





**Figure 2.** Global average depth profile of  $\text{N}_2\text{O}$  concentration (in  $\text{nmol L}^{-1}$ ) from the MEMENTO database (dots) (Bange et al., 2009), P.TEMP (blue) and P.OMZ (red). Model parameterizations are averaged over the 1985 to 2005 time period from the historical simulation.

Oceanic  $\text{N}_2\text{O}$  emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

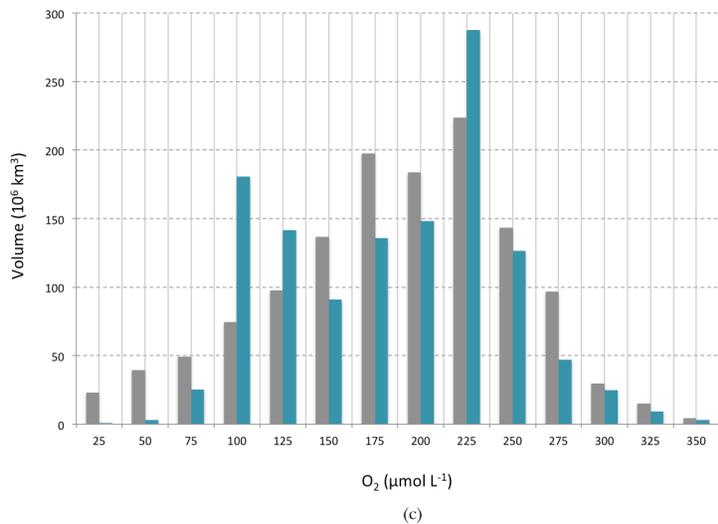
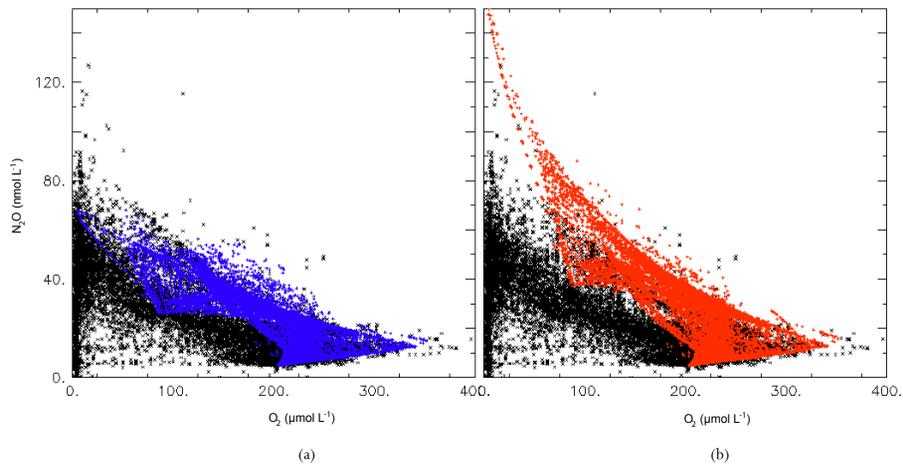
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





Oceanic  $\text{N}_2\text{O}$   
emissions in the 21st  
century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Figure 3.** Relationship between O<sub>2</sub> concentration (in μmolL<sup>-1</sup>) and N<sub>2</sub>O concentration (in nmolL<sup>-1</sup>) in the MEMENTO database (black) (Bange et al., 2009), compared to model **(a)** P.TEMP (blue) and **(b)** P.OMZ (red) parameterizations averaged over the 1985 to 2005 time period from the historical simulation. **(c)** Distribution of O<sub>2</sub> concentration in NEMO-PISCES 1985 to 2005 averaged time period (blue) compared to the oxygen corrected World Ocean Atlas (grey) from Bianchi et al. (2012).

## BGD

11, 16703–16742, 2014

### Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

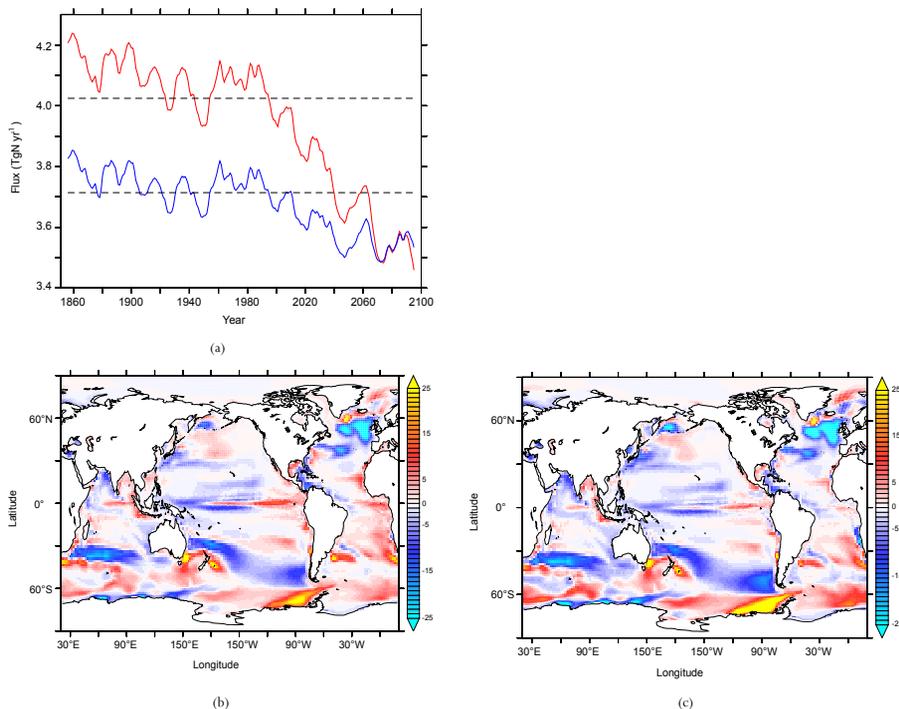
Printer-friendly Version

Interactive Discussion



## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.



**Figure 4.** (a) N<sub>2</sub>O sea-to-air flux (in TgN yr<sup>-1</sup>) from 1851 to 2100 in P.TEMP (blue) and P.OMZ (red) using the historical and future RCP8.5 simulations. Dashed lines indicate the mean value over the 1985 to 2005 time period. Change in N<sub>2</sub>O sea-to-air flux (mgN m<sup>-2</sup> yr<sup>-1</sup>) from the averaged 2080–2100 to 1985–2005 time periods in future RCP8.5 and historical simulations in (b) P.TEMP and (c) P.OMZ parameterizations.

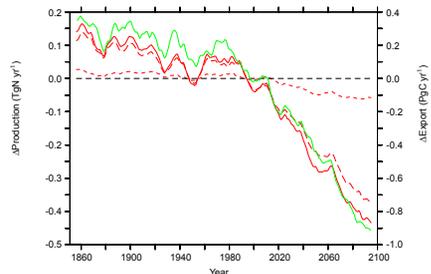
[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

# BGD

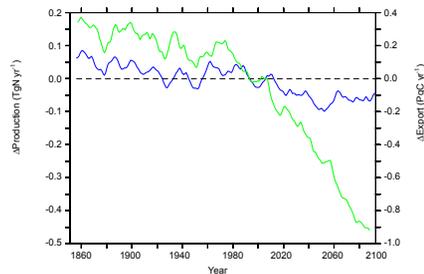
11, 16703–16742, 2014

## Oceanic N<sub>2</sub>O emissions in the 21st century

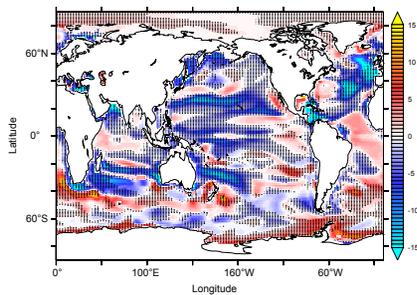
J. Martinez-Rey et al.



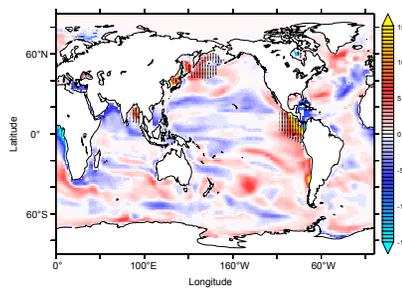
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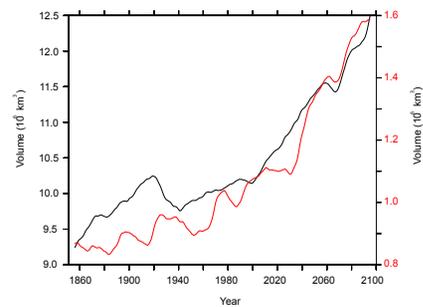
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(e)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

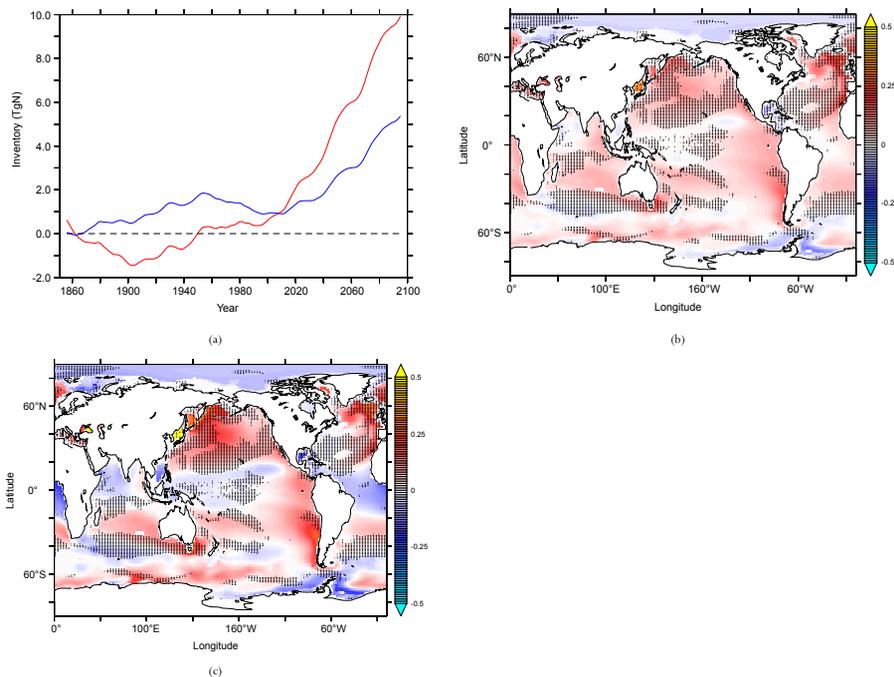
Interactive Discussion



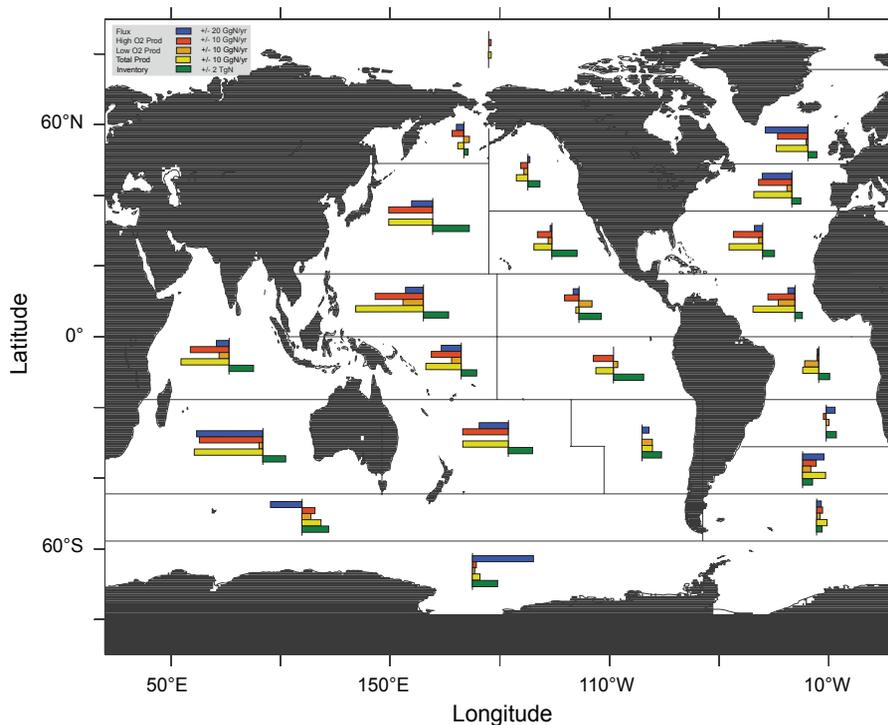


## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.



**Figure 6.** (a) Anomalies in N<sub>2</sub>O inventory (in Tg N) from 1851 to 2100 in P.TEMP (blue) and P.OMZ (red) using the historical and future RCP8.5 simulations in the upper 1500 m. Change in vertically integrated N<sub>2</sub>O concentration (in mg N m<sup>-2</sup>) in the upper 1500 m using NEMO-PISCES model mean from the averaged 2080–2100 to 1985–2005 time periods in future RCP8.5 and historical scenarios respectively in (b) P.TEMP and (c) P.OMZ. Hatched areas indicate regions where mixed layer depth is reduced by more than 5 m in 2080–2100 compared to 1985–2005.



**Figure 7.** Change in the whole water column in  $\text{N}_2\text{O}$  sea-to-air flux (blue), high- $\text{O}_2$  production pathway (red), low- $\text{O}_2$  production pathway (orange), total  $\text{N}_2\text{O}$  production (yellow) and  $\text{N}_2\text{O}$  inventory (green) for P.OMZ from the averaged 2080–2100 to present 1985–2005 averaged time period in the NEMO-PISCES historical and future RCP8.5 simulations (based on Mikaloff-Fletcher et al. (2006) oceanic regions).

**Oceanic  $\text{N}_2\text{O}$  emissions in the 21st century**

J. Martinez-Rey et al.

[Title Page](#)

[Abstract](#) | [Introduction](#)

[Conclusions](#) | [References](#)

[Tables](#) | [Figures](#)

[◀](#) | [▶](#)

[◀](#) | [▶](#)

[Back](#) | [Close](#)

[Full Screen / Esc](#)

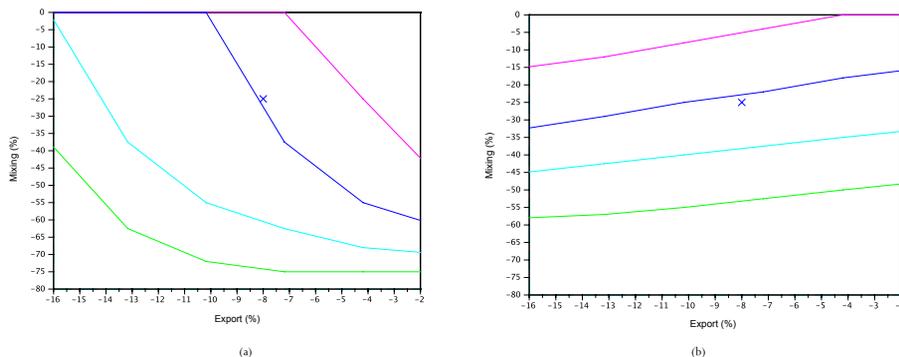
[Printer-friendly Version](#)

[Interactive Discussion](#)



## Oceanic N<sub>2</sub>O emissions in the 21st century

J. Martinez-Rey et al.



**Figure 8.** Constant regimes of **(a)** N<sub>2</sub>O sea-to-air flux (in percentage of the historical flux: 95% pink, 90% blue, 85% cyan and 80% green) and **(b)** N<sub>2</sub>O concentration in the deep (in percentage of the historical concentration: 90% pink, 110% blue, 125% cyan and 150% green) in 2100 as a result of a reduction in the export coefficient  $\varepsilon$  (in %) and in the mixing coefficient  $\mu$  (in %) in the box model.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

