Modelling the oceanic production of the greenhouse gas N_2O
Master's thesis project
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1 Motivation and Background

Nitrous oxide N_2O is, together with carbon dioxide and methane, one of the greenhouse gases in earth's atmosphere that has been increasing over pre-industrial concentrations due to activities of mankind. It is also involved in the depletion of stratospheric ozone. Per mole, nitrous oxide is 298 times as efficient as CO_2 in trapping long-wave radiation, and its increase between the years 1750 and 2018 from 279 parts per billion (ppb) to 331 ppb is responsible for about 6% of the current anthropogenic radiative forcing (Myhre et al, 2013).

The atmospheric life-time of N_2O is fairly long (116 ± 9 years, Prather et al, 2015); its increase in the atmosphere over the last decades is hence driven by changes in its production. This production, both on land and in the ocean, is mostly related to two bacterially mediated transformations of nitrogen, denitrification and nitrification (Figure 1). These processes are affected in several ways by factors such as substrate availability (which are affected e.g. by human fertilizer use), temperature, and oxygen levels, which are changing with climate.

To describe possible feedbacks between climate change and the atmospheric concentration of greenhouse gases, climate models now typically include a model description of the cycling of carbon (standard in the 6th IPCC report). A model description of the other greenhouse gases CH_4 and N_2O is so far done only by very few global climate models (Séférian et al., 2020).

The ocean is one of the largest natural sources of N_2O, and there is a strong potential for climate change feedbacks of N_2O emissions in response to ocean warming and deoxygenation. For assessing these possible feedbacks, ocean biogeochemical models are needed that are able to describe the present-day role of the ocean in N_2O cycling.

2 Outline for a Master's Project

The aim of this project would be first to implement a description of the production and outgassing of N_2O in the ocean into the existing global biogeochemical ocean model FESOM2-REcoM3 (Gürses et al, 2023, subm.). This is a coupled model of the physical ocean state and circulation (FESOM), with an added biogeochemical module (REcoM) which describes the cycling of carbon, nitrogen, silicon and iron by the lower levels of the marine ecosystem. This model can also be run as part of the AWI earth system

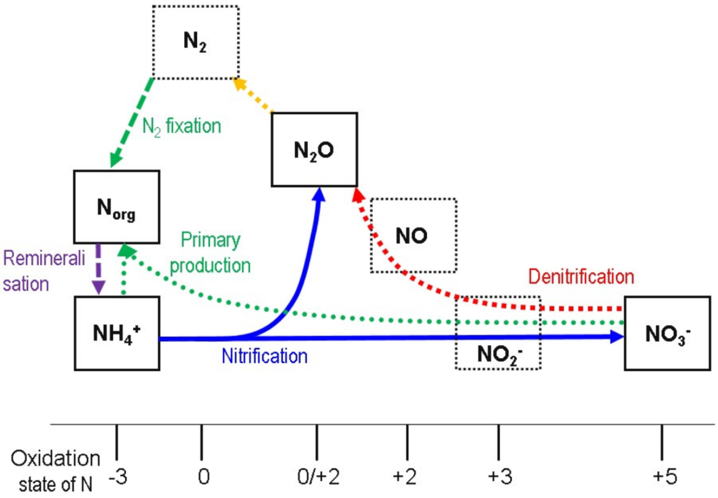

Figure 1: Processes that lead to the production of nitrous oxide in the ocean: Nitrification is the the bacterially mediated oxidation of NH_4^+ to NO_3^- and leads to some loss in the form of N_2O. Denitrification is the use of nitrate instead of oxygen by bacteria as electron acceptor to oxidise organic carbon, and happens primarily in oxygen-poor parts of the water column and sediments. It is actually a sequence of four reactions, through the intermediates NO_2^-, NO and N_2O. In almost total absence of O_2, denitrification proceeds up to the the terminal product N_2 gas, i.e. the N_2O that is produced as intermediate, is consumed. In the presence of low, but non-vanishing concentrations of O_2, however, the process can stop before ths last step, leading to a net production of N_2O (Cohen and Gordon, 1978). Figure taken from Buitenhuis et al., 2018.

model, by coupling it to a model of the atmosphere and the terrestrial ecosystem, but this would not be done within this limited project.

This implementation requires three steps: First, the current state variable 'dissolved inorganic nitrogen' needs to be replaced by three different variables nitrate NO_3^-, ammonia NH_4^+ and N_2O, that are all advected and diffused by the ocean circulation model. Second, a model description of the transformations between these variables, nitrification and denitrification, needs to be implemented. Here we can closely follow how this is done in a different biogeochemical model (Buitenhuis et al, 2018). And third, a description of the gas exchange flux for N_2O needs to be implemented, that closely matches that for CO_2, but with a different solubility for N_2O (Weiss and Price, 1980).

After the implementation is done, the model can be integrated forward with atmospheric forcing for the recent decades. This is done routinely in our group (it requires access to the new AWI supercomputer, though), but will then give output on the distribution of N_2O within the ocean, and the flux of N_2O beween ocean and atmosphere. This output should be visualized and described, and be compared to the available data on the distribution of N_2O in the ocean, which is available in the MEMENTO database (Zamora et al, 2012), and with estimates of the total air-sea flux of N_2O (Tian et al., 2020).

Reasons for matches and mismatches to the observed distribution of oceanic N_2O should be discussed; at this stage it might be useful also to vary some of the rates involved in the description of nitrification and denitrification, and re-run the model, to understand the models sensitivities. Finally, the model output could contribute to the N_2O budget that regularly compiled and updated by the Global Carbon Project (Tian et al., 2020), similar to the nowcasting of atmosphere-ocean CO_2 fluxes (Friedlingstein et al, 2020).

3 Practical Steps and Timeline

- Getting to know the model code, how to compile and run it (month 1).
- Reading background literature (months 1-2).
- Splitting of the DIN variable in the model into NO_3^{2-}, NH_4^+ and N_2O, and implementation of nitrification, denitrification, and gas exchange (months 2-3).
- Running the model for present-day climate, with possibly a few (on the order of 2-4) sensitivity runs (months 3-6).
- Visualization and analysis of the model output, and comparison to literature data (months 4-7).
- Writing of the thesis (months 3, and 7-9).

4 What you get and what you need

This project is a modelling project, and the work has basically three different parts. First, the biogeochemical model code has to be extended a little bit, to include a representation of nitrification and denitrification processes. The amount of coding that has to be done here is fairly limited, but one has to read parts of the model code, which is written in FORTRAN90 and extend it. Second, the model has to be run on the AWI supercomputer. This is a unix/linux environment. And finally, the model results have to be analyzed and visualized; a python library exists for that.

So, after finishing the project you will have gained experience with a some FORTRAN programming, you will have worked in linux on a high-performance computer, and used python for analysis. Some previous experience in any of these skills is of course helpful, but it could also be some previous experience in Matlab or R.

You will get support with any of the these skills in our group at AWI, and also regular support in structuring your reading and working from us. We are a friendly group of around 10 modellers, from PhD students and guest students to researchers, and we meet once a week to chat. Part of the work could be done from home, but it is our experience that regular personal contact helps in getting difficulties solved quickly, so we recommend to be at AWI, Bremerhaven at least two days a week.

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