Nitrous oxide's ozone destructiveness under different climate scenarios

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Abstract
Nitrous oxide (N_2O) is an important greenhouse gas and ozone depleting substance as well as a key component of the nitrogen cascade. While emissions scenarios indicating the range of N_2O's potential future contributions to radiative forcing are widely available, the impact of these emissions scenarios on future stratospheric ozone depletion is less clear. This is because N_2O's ozone destructiveness is partially dependent on tropospheric warming, which affects ozone depletion rates in the stratosphere. Consequently, in order to understand the possible range of stratospheric ozone depletion that N_2O could cause over the 21st century, it is important to decouple the greenhouse gas emissions scenarios and compare different emissions trajectories for individual substances (e.g. business-as-usual carbon dioxide (CO_2) emissions versus low emissions of N_2O). This study is the first to follow such an approach, running a series of experiments using the NASA Goddard Institute for Space Sciences ModelE2 atmospheric sub-model. We anticipate our results to show that stratospheric ozone depletion will be highest in a scenario where CO_2 emissions reductions are prioritized over N_2O reductions, as this would constrain ozone recovery while doing little to limit stratospheric NO_x levels (the breakdown product of N_2O that destroys stratospheric ozone). This could not only delay the recovery of the stratospheric ozone layer, but might also prevent a return to pre-1980 global average ozone concentrations, a key goal of the international ozone regime. Accordingly, we think this will highlight the importance of reducing emissions of *all* major greenhouse gas emissions, including N_2O, and not just a singular policy focus on CO_2.

Key Words
Nitrous oxide; stratospheric ozone depletion; climate change; emissions scenarios

Introduction
Nitrous oxide (N_2O) is the third most important greenhouse gas and the most abundantly emitted ozone depleting substance. While N_2O is currently listed under the international climate regime, the lack of attention devoted to it has led to an increasing number of calls for the international ozone regime to consider taking it on (Kanter et al. 2013; UNEP 2013). However, the extent to which N_2O may impact stratospheric ozone levels over the course of the 21st century and beyond is uncertain. This is because its ozone destructiveness is strongly influenced by tropospheric temperatures, which have steadily increased since the industrial revolution due to increasing anthropogenic emissions of a suite of greenhouse gases (Rosenfield & Douglass, 1998). Rising temperatures in the troposphere cools the stratosphere, slowing down ozone loss, but also slowing down the production and increasing the destruction of nitric oxide (NO), which is the breakdown product of N_2O that destroys stratospheric ozone. However, recent efforts to coordinate international action on climate change (such as the Paris Climate Agreement) could limit tropospheric temperature increases to 2^{o}C or less, which would limit the potential of a warming climate to accelerate stratospheric ozone recovery. In either case, it is critical to better understand how different greenhouse gas emissions trajectories and their impacts on global surface temperature might impact future stratospheric ozone recovery. This study uses the atmospheric sub-model of ModelE2, a new version of the NASA Goddard Institute for Space Sciences (GISS) coupled general circulation model, to evaluate N_2O's ozone destructiveness under different climate scenarios.

Almost all the studies that have analyzed N_2O's ozone destructiveness under different climate scenarios assume that the emissions of every greenhouse gas (carbon dioxide (CO_2), methane (CH_4), N_2O and fluorinated gases) follow the same storyline, be it business-as-usual (e.g. RCP 8.5, SRES A1, SRES A2), moderate (RCP 6 & RCP 4.5) or ambitious (RCP 2.6, SRES B1, SRES B2) mitigation pathways (Plummer et al. 2010; Oman et al. 2010; Portmann et al. 2012; Stolarski et al. 2015). In these scenarios, if CO_2 emissions follow a business-as-usual trajectory then N_2O emissions are assumed to as well. Conversely, if CO_2 emissions are dramatically reduced as a result of ambitious mitigation efforts, then N_2O emissions are too. See Figure 1 for an estimate of stratospheric ozone concentrations under the mostly recently developed climate scenarios.

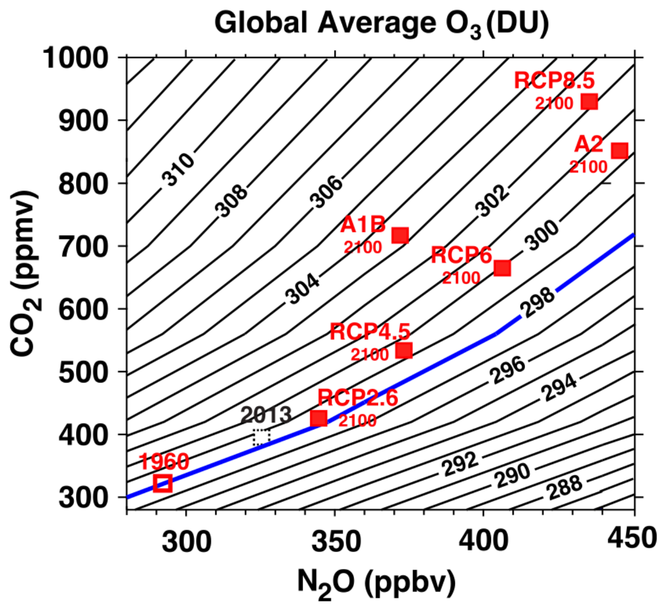

Figure 1. Global average ozone (in Dobson Units – DU) under different atmospheric concentrations of CO_2 and N_2O. Values in red are projected ozone concentrations in 2100 under different climate scenarios. The blue line represents global average ozone concentrations in 1960. Adapted from Stolarski et al. 2015.

However, the majority of CO_2 emissions come from fossil fuel combustion, with completely different sectors and solutions compared to N_2O emissions. The majority of N_2O comes from the agricultural sector and the inefficient management of nitrogen. Consequently, it is conceivable that the emissions trajectories for these substances could differ substantially – certain sectors might be prioritized over others, and certain strategies might be more cost-effective or socially acceptable than others. Revell et al. (2012) addresses one aspect of this idea by comparing the ozone impacts of different N_2O emissions trajectories (ranging from business-as-usual to ambitious mitigation) under a business-as-usual CO_2 emissions scenario (SRES A1B). In such a decoupled emissions scenario, a cooling stratosphere dampens N_2O's ozone destructiveness. While certainly interesting, this study keeps all non-N_2O emissions on one business-as-usual storyline. We build and expand upon this work by evaluating the ozone impacts of a range of N_2O emissions trajectories against a range of non-N_2O emissions trajectories. Consequently it allows us to evaluate a broader spectrum of N_2O's potential future ozone impacts. For example, it is possible that policy-makers decide to prioritize CO_2 reductions (leading to a RCP 4.5 or even RCP 2.6 emissions pathway) while doing little to reduce N_2O emissions (RCP 8.5). This possibility is reinforced by recent studies suggesting that in scenarios with ambitious mitigation targets, non-CO_2 emissions (including N_2O) could become the largest portion of remaining greenhouse gas emissions (Gernaat et al. 2015) – implying that their mitigation potential is limited compared to CO_2. This could have significantly different implications for N_2O's future ozone destructiveness compared to a scenario where N_2O emissions reductions are prioritized at the expense of CO_2.

Methods

This study uses the atmospheric sub-model of ModelE2.1S-TCADI, a new version of the NASA Goddard Institute for Space Sciences (GISS) coupled general circulation model. The atmospheric sub-model has 2^o x 2.5^o horizontal resolution and 96 vertical layers, with the model top near the stratopause at 0.1 hPa. It simulates orbital variability, solar variability, volcanic aerosols, greenhouse gas emissions, stratospheric ozone depletion, tropospheric ozone changes, the direct and indirect sulfate, nitrate, black carbon, and organic aerosol changes (including the impact of black carbon on snow and ice albedo), and land use/land cover changes (see Schmidt et al. 2014 for a more detailed description of the model physics). We plan to run 16 basic experiments comparing stratospheric ozone levels under different combinations of N_2O and CO_2 emissions trajectories out to 2100 (Table 1).

Table 1. The experiments we plan to run in order to get a range of potential stratospheric ozone depletion from N_2O over the 21st century under different climate scenarios.

Experiment	N_2O	CO_2
1	RCP 2.6	RCP 2.6
2	RCP 2.6	RCP 4.5
3	RCP 2.6	RCP 6.0
4	RCP 2.6	RCP 8.5
5	RCP 4.5	RCP 2.6
6	RCP 4.5	RCP 4.5
7	RCP 4.5	RCP 6.0
8	RCP 4.5	RCP 8.5
9	RCP 6.0	RCP 2.6
10	RCP 6.0	RCP 4.5
11	RCP 6.0	RCP 6.0
12	RCP 6.0	RCP 8.5
13	RCP 8.5	RCP 2.6
14	RCP 8.5	RCP 4.5
15	RCP 8.5	RCP 6.0
16	RCP 8.5	RCP 8.5

Results & Discussion

While we do not yet have publishable results for this set of experiments, if our intuitions are correct then we expect to see significantly greater stratospheric ozone depletion in a scenario where CO_2 reductions are prioritized over N_2O reductions (i.e. where CO_2 emissions follow an ambitious mitigation pathway, as represented in RCP 2.6, versus N_2O emissions following a RCP 8.5 trajectory). Conversely, we expect to see the least stratospheric ozone depletion in a scenario where N_2O reductions are prioritized over CO_2 reductions. We think the former scenario (low CO_2, high N_2O) is a particularly conceivable policy outcome given the focus of current policy discussions on point source emissions such as transport and industry, with little focus on non-point sources such as agriculture. Moreover, nitrogen inputs are fundamental to modern food production and food security, and so efforts to improve their management is likely to be met with trepidation, particularly in developing countries.

Conclusion

N_2O's impact on stratospheric ozone depletion in the 21st century and beyond will not only depend on its own emissions, but also on the extent of tropospheric warming, which is expected to depend largely on greenhouse gas emission trends. Consequently, it is important to improve our understanding of the range of possible stratospheric ozone depletion from N_2O under different greenhouse gas emissions scenarios. For the first time, this study will present decoupled climate scenarios with experiments comparing N_2O and CO_2 (the dominant anthropogenic greenhouse gas) under different emissions trajectories. We expect to find that stratospheric ozone depletion will be greatest in a scenario where CO_2 emissions reductions are prioritized and N_2O emissions are not. This is not inconceivable given the current complexion of national and regional climate policies, which focus on point source emissions such as transport and industry, with little attention to agricultural GHG sources, such as the inefficient use of fertilizer and manure. It remains to be seen whether this will impact the goal of the international ozone regime to return to pre-1980 levels of stratospheric ozone.

References

Gernaat D.E.H.J et al. 2015. Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change*. 33:142–153

Kanter D. et al. 2013. A post-Kyoto partner: Considering the stratospheric ozone regime as a tool to manage nitrous oxide. *P. Natl. Acad. Sci. USA*. 112:4451-4457

Oman L.D. et al. 2010. Mechanisms and feedback causing changes in upper stratospheric ozone in the 21st century. *J. Geophys. Res.* 115 D05303
Plummer D.A. et al. 2010. Quantifying the contributions to stratospheric ozone changes from ozone depleting substances and greenhouse gases. *Atmos. Chem. Phys.* 10.18 8803–20
Portmann R., Daniel J., and Ravishankara A.R. 2012. Stratospheric ozone depletion due to nitrous oxide: influences of other gases. *Phil.Trans. R. Soc. B* 367:1256–64
Revell L.E. et al. 2012. The effectiveness of N_2O in depleting stratospheric ozone. *Geophysical Research Letters,* 39, L15806
Rosenfield J.E. & Douglass A.R. 1998. Doubled CO_2 effects on NOy in a coupled 2D model. *Geophysical Research Letters,* 25(23):4381-4384
Schmidt G.A. et al. 2014. Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive. *Journal of Advances in Modeling Earth Systems*. 10.1002/2013MS000265
Stolarski R.S. et al. 2015. Impact of future nitrous oxide and carbon dioxide emissions on the stratospheric ozone layer. *Environmental Research Letters,* 10: 034011
UNEP. 2013. Drawing Down N_2O to Protect Climate and the Ozone Layer. A UNEP Synthesis Report. (Nairobi: United Nations Environment Programme)