

Author Comment to Referee #1 (Daniele Visioni)

ACP Discussions doi:10.5194/acp-2020-747

(Editor - Farahnaz Khosrawi)

‘Potential of future stratospheric ozone loss in the mid-latitudes under climate change and sulfate geoengineering’

We thank Daniele Visioni for detailed guidance on how to revise our paper. Following the reviewers advice we renamed the "climate change" scenario to "global warming" scenario. Further, we took more care by using the term "GLENS" in the discussion and specified the future scenarios (geoengineering and global warming) more precisely. Our reply to the reviewer comments is listed in detail below. Questions and comments of the referee are shown in italics. Passages from the revised version of the manuscript are shown in blue. Comments of the reviewer, which are not listed below, were applied to the manuscript as the reviewer suggested. In general, comments not shown here refer to typos and grammar mistakes.

Referee Comments

This study by Robrecht et al. focuses on analysing the conditions over which heterogeneous chlorine activation and its subsequent effect on ozone concentration in the mid-latitudes might happen if stratospheric aerosols injections are applied. To do so, the authors use both direct simulations results from CESM1(WACCM) and box-model simulations from the Chemical Lagrangian Model of the Stratosphere (CLaMS). While the impact is found to be rather minimal, the analyses presented in this paper are very nicely described, are scientifically robust and definitely of interest to the scientific community. The paper is of high quality and deserves publication on ACP. I have some minor suggestions that I list below, and after they are addressed the manuscript can be accepted promptly.

General remark: Throughout the entire manuscript, the authors define the

RCP8.5 cases as the “climate change” cases, whereas the GLENS geoengineering scenario is defined as “geoengineering scenario”. They also are not always consistent with the names they use to define the two scenarios. I think that’s not entirely correct, as a definition, and could be a bit misleading. Would climate change under RCP8.5? Of course, as a consequence of high GHGs mixing ratios. But contrasting “climate change” with geoengineering gives the impression that what GLENS (and geoengineering in general) does is “cancels out” climate change. It doesn’t, and plenty of GLENS studies have shown that, while smaller than those produced by the warming alone, geoengineering does produce some changes in the surface climate. So, for clarity, I would suggest the authors use a more precise definition for the RCP8.5 scenario (i.e. “increased surface warming”). Even just calling it “RCP8.5” would be better.

We changed the name of the “climate change” scenario to “global warming” throughout the paper. Further, the terms for both GLENS scenarios are used more precisely in the paper and are more specifically introduced (p.6, 1.5–9 of the revised manuscript):

GLENS provides a comprehensive global data set assuming two different potential scenarios and covering the years 2010–2100. The GLENS scenario, which follows the RCP8.5 emission pathway, will lead to an increased warming of the global mean surface temperature in future. Hence, this scenario is referred to as the “global warming scenario” in this study. The GLENS future scenario, which assumes the RCP8.5 emission pathway together with stratospheric SO₂ injections to keep the global mean surface temperature from warming, is here referred to as the “geoengineering scenario”.

Page 1 Line 29: I would suggest also citing some of the results from CCMI, for instance discussing the sensitivity of ozone changes to various ODSs and GHGs, Morgenstern et al. (2018)

We added 2 sentences with the results of Morgenstern et al. (2018) at p. 1 l. 28–32 of the revised manuscript:

However, comparing simulations of different models Morgenstern et al. (2018) show that an increase in CH₄ can also lead to an ozone reduction in the low-

ermost stratosphere. Increasing N_2O mixing ratios lead to an increase in ozone for most model simulations Morgenstern et al. (2018) compared, while more CO_2 likely causes an ozone reduction in the tropical and subtropical lowermost stratosphere.

Page 5 Line 23: maybe better to specify it's "surface" temperatures that GLENS tries to manage?

We agree with the reviewer and clarify that the temperature targets in the GLENS geoengineering scenario are for the surface temperature (p. 5, l. 25–27 of the revised manuscript).

The geoengineering scenario of GLENS is based on the RCP8.5 scenario, but aims to hold the global mean temperature, the inter-hemispheric temperature gradient and the equator-to-pole gradient at the Earth surface at the level to the year 2020 by applying stratospheric sulfur injections (for more details see Kravitz et al. (2017)).

Page 5 Line 31: in CESM1(WACCM), yes, but other models need to inject upward to 20 Tg-SO₂ to get the proper AOD (see Timmreck et al. (2018) and references therein). So either specify that that's what WACCM needs, or that there's a range of uncertainty in this.

We adapted that sequence in the revised manuscript (p. 5, l. 32 – p. 6, l. 4):

To reach the temperature targets, in the GLENS geoengineering scenario more than 50 Tg SO_2 would have been emitted at the end of the 21st century. This is five times the emitted amount of sulfur by the Mt. Pinatubo eruption in the year 1992 (Tilmes et al., 2018). However, other models than the WACCM do need to inject other amounts of SO_2 into the stratosphere to keep the global mean surface temperature constant (Timmreck et al., 2018). Hence, it should be noted that generally there is a certain range of uncertainty in the SO_2 amount needed.

Page 6 Table 1: I think the names of the scenarios should be more consistent

between experiments, as I said before. First of all, the 2010-2020 period is still under RCP8.5, since the emissions do vary even in that decade between the RCPs. Second, if C2040 is defined as “Climate Change following the RCP8.5 emission pathway” (although here I would use “surface temperatures increase”), then consistently F2040 should be defined as “Sulfate geoengineering to maintain temperatures at C2010 levels” (but it’s actually 2010-2030, so it should be more specific) and similarly for F2090. Or another idea could be to have a column for “Underlying Emission Scenario” (that is always RCP8.5), a column for “Global T increase” (that would be > 0 for the C simulations and ~ 0 for the F simulations) and a column for “Stratospheric SO₂ injected” (that would be $= 0$ for the C simulations and > 0 for the F simulations). This would give the reader unfamiliar with GLENS an estimate at a glance of the amount of warming and of intervention that it’s being considered here. Overall, the authors are free to do as they wish, but I strongly suggest making this table more useful to the reader.

We thank the reviewer for the advise and extended Tab. 1 in the manuscript. Further, we declared the cases more specific and consistent throughout the paper.

Table 1: Overview of the cases analysed in this study. In addition to the years considered, the underlying emission scenario in the GLENS simulation, the global temperature increase (referred to 2010–2020) and the SO₂-amount injected by that time period are given for each case.

Case	Years	GLENS scenario	emission scenario	global temperature increase / K	SO ₂ injected / Tg
C2010	2010–2020	global warming	RCP8.5	0.0	0.0
C2040	2040–2050	global warming	RCP8.5	1.8	0.0
C2090	2090–2100	global warming	RCP8.5	6.0	0.0
F2040	2040–2050	geoengineering	RCP8.5	−0.1	14.4
F2090	2090–2100	geoengineering	RCP8.5	0.1	49.0

The cases are introduced at p. 6, l. 12–17 of the revised version of the manuscript:

In total 5 cases are analysed which are determined through the GLENS scenario and the decade. The case C2010 describes conditions in the early 21st century (2010–2020) based on the GLENS global warming scenario.

The conditions for the mid (2040–2050) and the end (2090–2100) of the 21st century following the global warming scenario are referred to as case C2040 and C2090, respectively. The cases of the geoengineering scenario are named F2040 and F2090 for the mid and the end of the 21st century, respectively (“F” stands for the “Feedback” mechanism of the SO₂ injections). An overview of the considered cases is given in Tab. 1 together with the global mean temperature increase reached in that case comparing to the conditions of the years 2010–2020 and the injected amount of SO₂.

Page 6 Line 15 or thereabout: is the spatial range chosen for a specific purpose (i.e. we have measurements over that area) or just as an example because (clearly) considering the entire latitudinal band would be too much calculations? From reading further on, it is clear it is the former, so it should be specified in here too.

We specified the purpose for the selection of the considered area (p. 6, l. 18–20 of the revised version of the manuscript):

GLENS results are selected for a latitude range of 30.6–49.5°N and a longitude range of 72.25–124.75°W (grey marked in Fig. 1, left), because for this area the reliability of the GLENS C2010 results could be analysed in comparison with aircraft measurements of the SEAC⁴RS and START08 campaigns.

Page 8 Table 2: “For a better overview in this paper, the pressure ranges are allocated to a pressure level” I find this phrase very hard to parse, even if I can catch the meaning. Should be rewritten.

We rewrote the sentence in the caption of Tab. 2 (p. 9, l. 2–3 in the revised version of the manuscript).

For a better overview in this paper, pressure levels are used to describe the pressure ranges (e.g. 80 hPa level for the pressure range 70–90 hPa).

Page 8, Line 5: “tropospheric character” doesn’t really mean much. Maybe “characteristic”?

We changed the sentence as follows (p.8, l.1–2 of the revised version of the manuscript):

Furthermore, based on the ozone mixing ratio considered air masses can be divided in those with a chemical composition of air masses typically for the troposphere (low ozone) and those with a chemical composition more typically for the stratosphere (high ozone).

Page 12 Lines 2-5: If the “higher ozone smog production” is a result of RCP8.5 emissions, shouldn’t the same also be observable in GLENS, given the underlying emissions are the same? Later, on line 5, should specify that the BDC changes transporting more air downward are true at the considered latitudes, not everywhere.

We agree with the reviewer that a higher ozone smog formation would be also expected in the GLENS geoengineering scenario, because the emissions of CO₂ and CH₄ are the same as in the RCP8.5 scenario. However, we did not find an obvious reason, for the lower ozone mixing ratios in the geoengineering cases. Because of more extensive research on this question is not in the scope of our study, we removed that sentence from the paper.

Regarding the changes in the Brewer-Dobson-Circulation (BDC), we added that the statement refers to the considered latitude range (p. 12, l. 12–16 of the revised version of the manuscript).

For cases with global warming, the ozone mixing ratio is significantly higher in case C2040 (yellow) and C2090 (green) especially for low E90 concentrations. The enhancement of ozone in the mixing layer could be caused by changes in atmospheric transport or chemistry. Global warming is expected to increase upper stratospheric ozone and accelerate the BDC. In the considered latitude range, this leads to more ozone transported downwards in the lowermost stratosphere from high altitudes (Iglesias-Suarez et al., 2016).

Page 18 Line 1-2: the HCl absorption by the liquid aerosols is an interesting point. Some mention of the fact that this has been observed and discussed for volcanic eruption could be of interest to the reader (see Tabazadeh and Turco, 1993) to back up this point.

We thank the referee for recommending us to cite Tabazadeh and Turco (1993). We mentioned the results of that study (p. 17, l. 21–23 in the revised version of the manuscript):

HCl uptake into supercooled water particles was also found to occur after volcanic eruptions resulting in an "HCl scavenging", which may protect the ozone layer (Tabazadeh and Turco, 1993).

Page 21 Line 17: maybe "conservation" is a clearer term than "maintenance"?

We substituted the term maintenance with the term conservation (p. 21, l. 26–27 in the revised version of the manuscript).

In the lowermost stratosphere, the duration of conservation for conditions causing chlorine activation is not yet known.

Line 34: this makes it sound like the geoengineering scenario in GLENS prescribes a reduction of ODS. That reduction is prescribed in the underlying RCP scenarios, more in general. This is especially confusing considering the authors sometimes use GLENS to identify the geoengineering scenario, sometimes both future scenarios.

Throughout the paper, we took care to specify more precisely the discussed GLENS scenario and the considered case. Here, we adjusted the sequence to make clear that ODS are reduced in both GLENS scenarios in the future (p. 22, l. 10–11 of the revised version of the manuscript).

The increasing ozone formation in the future may be related to the reduction of ODS implemented in both GLENS scenarios.

Throughout the Discussion session, it is hard to understand what the authors mean by GLENS. The geoengineering scenario? The RCP8.5 one? Should be clarified.

We thank the referee for this remark. As said before, throughout the manuscript we took care to specify more precisely the discussed GLENS scenario and the considered case.

Page 31 Line 15: “few ozone” is not really correct. “Not much”, or “scarcely any” would be more correct.

Because we did not analyse the temperature bias of GLENS extensively, it might be possible that the temperatures assumed in our study are too high. Performing case studies with lower temperatures yields that lower temperatures would increase the potential impact of heterogeneous chlorine activation on ozone. Because of this range of uncertainty, we decided to keep “few ozone” here.

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