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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Ozone changes under solar geoengineering: implications for UV exposure and air quality" *by* P. J. Nowack et al.

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We thank the reviewer very much for the positive and constructive comments, which we found very helpful to improve our manuscript.

Below, we reply point-by-point to the referee's comments (normal font) in bold, italic. Any references to pages and line numbers made by us refer to the published online version of the discussion paper and may have changed in the revised version.

This global modeling study investigates the mechanisms and processes where solar radiation management (SRM) geoengineering techniques can impact surface UV and

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tropospheric chemistry. The implied SRM technique is that of space mirrors, where the solar constant is turned downwards to emulate a blocking out of the sun's rays, the magnitude of which tuned to match the radiative forcing from 4xCO2 (this is the so called G1 experiment).

The authors present some "standard results" (e.g. spatial pattern of temperature changes) before discussing chemical and related impacts more thoroughly. Key results include how a cooling stratosphere couples with reduced water vapor to drive ozone increases in the G1 simulations. The G1 simulations also increase tropospheric ozone, driven mainly by reduced water vapor (reduced OH production) and UV penetration (due to higher stratospheric ozone). The authors also highlight that the reduced UV could be important for human health through reduced vitamin D production.

Overall, I feel that this study positively adds to the growing literature analyzing the impacts of geoengineering techniques. Composition and UV impacts have not been studied in detail, and, while the scenarios are not necessarily ideal (e.g. using preindustrial levels of ozone precursors; as also noted by another reviewer), the authors note these weaknesses, and I think that it provides a good basis to compare future work against. In summary, I would be happy to recommend this for publication after the authors have considered my minor comments/corrections below (mostly very minor).

Specific comments (page and line numbers refer to the original Word version)

- P1, L14: Why italicize geoengineering?

This was thought to put some emphasis on the central idea under study. We do not feel strongly about this emphasis, so we leave it out in the revised version.

- P2, L1: "However, despite..." – I feel this sentence rather trivializes an extremely complex issue. It is not possible to just turn off CO2 emissions without all kinds of

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(nonatmospheric) consequences!

We certainly did not want to trivialise. We have changed the text slightly to read: "It is recognized that reducing greenhouse gas emissions is difficult so that, under these circumstances, there is discussion on alternative measures to counteract the effects of climate change".

- P2, L2: It's not just researchers talking about GE

The sentence given in the previous reply circumvents this specification as well.

- P2, L16: Suggest: "The central problem..." -> "A major issue..."

Done.

- P2, L18: Full stop after "Earth system" and then start a new sentence.

Done.

- P3, L11: Might want to be clear how UV (or other GE-related factors) can influence surface ozone

In the revised manuscript, we now have a separate short introduction for the potential tropospheric ozone changes driven by changes in the stratosphere. It reads:

"Surface ozone is a pollutant, which has been associated both with diseases of the respiratory system and crop damage (Avnery et al., 2011; Silva et al., 2013). Many countries have introduced emission controls aimed at reducing emissions of tropospheric ozone precursors. However, tropospheric surface ozone depends not just on in situ emissions but also on processes in the stratosphere.

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For example, changes in stratospheric ozone will impact tropospheric chemistry by altering the photolysis environment in the troposphere (Madronich et al., 2015). Similarly, the transport of ozone from the stratosphere is an important component of the tropospheric ozone budget (e.g. Holton et al., 1995; Neu et al., 2014). Any SRM scheme which affects the stratosphere could therefore also impact tropospheric composition."

- P3, L26: “Finally, section 4...”

Done.

- P4, L7: Ref for MetUM?

The atmosphere, ocean and sea-ice model versions and their coupling were described together in the HadGEM3 reference to Hewitt et al. (2011). For the atmosphere model, this paper is definitely the most appropriate one to cite. In order to avoid confusion, we add the citation a second time in the revised manuscript.

- P4, L12: comma after MetUM

Done.

- P4, L15-: Refs for these models?

In the revised version we also include some more original citations for the stand-alone ocean and sea-ice models even though the actual atmosphere-ocean-sea-ice coupled model used here is described in Hewitt et al. (2011).

- P4, L21-: Is aerosol chemistry included? Are there composition/climate feedbacks with CH4 and N2O? Clarify whether the photolysis scheme respond to clouds, ozone

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and solar flux?

The CLASSIC aerosol scheme is included in the model (Bellouin et al., 2011), which is not coupled to UKCA. Concerning composition-climate feedbacks with CH4 and N2O the model is fully interactive. The FastJX photolysis scheme is interactive with respect to clouds, ozone and solar flux, we have added the following sentences to clarify this:

"Ozone, nitrous oxide and methane are fully interactive in the model so that their changes feedback onto changes in radiation. [...] Photolysis in FastJX responds, inter alia, to ozone and solar flux as well as to multiple layers of clouds of varying degrees of thickness."

Bellouin, N. et al.: Aerosol forcing in the Climate Model Intercomparison Project (CMIP5) simulations by HadGEM2-ES and the role of ammonium nitrate, J. Geophys. Res., 116, D20206, doi:10.1029/2011JD016074, 2011.

- P5, Sect 2.2: I would be explicit that the CFC levels are (presumably) zero in the simulations.

We have added the following sentence to be more explicit about the settings:

"By design, the G1 experimental set-up does not include pre-defined changes in surface emissions of ozone depleting substances from anthropogenic sources (e.g. CFCs whose abundance is equal to zero in this set-up), or tropospheric ozone precursors."

- Also, would any putative space mirrors be uniformly efficient at all wavelengths?

Indeed, this is another idealised assumption. Possibly, mirrors could even be designed to dim some wavelengths more than others, similar to the wavelength-

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dependent reflective properties of aerosols. However, in practice, a uniformly dimming mirror would be most effective in terms of the radiative energy reflected per unit area (assuming the very hypothetical case of an actual implementation of space-mirror geoengineering). An only partially reflective mirror would let through certain wavelengths of light and thus a part of the potentially reflected energy incident on the mirror's surface. Space-mirror geoengineering would likely be strongly limited by (financial) resources to bring sufficient mirror surface area into space. Therefore, the mirror surface area would likely be the 'bottleneck' in any such operation, thus making uniformly (totally) reflective mirrors the most effective ones.

- P7, L6: Delete "rather"

Done.

- P7, L8: "heating by higher ozone levels"

Done.

- P7, L11: "in G1, as discussed below."

Done.

- P7, L33: why is NOx higher? Temperature effects?

The increased upper stratospheric NOx abundances are a net result of increased transport of the precursor species nitrous oxide (N2O) into the upper stratosphere from the troposphere under 4xCO2 due to changes in the strength of the Brewer-Dobson circulation (which are effectively reset in G1) and differences in chemical NOx production and loss, e.g. due to the reaction N2O+O(1D) (where

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O(1D) also changes significantly as highlighted in the manuscript), the coupling with the HOx cycle and last but not least temperature dependencies of the chemical reactions, see for example Revell et al. (2012) for an overview of the effects involved. We added the Revell et al. (2012) citation to the paper to highlight the issue.

Revell, L. E. et al. The effectiveness of N2O in depleting stratospheric ozone, Geophys. Res. Lett., 39(15), 1–6, doi:10.1029/2012GL052143, 2012.

- P8, L6-8: Is this because the BDC slows?

Yes, this is what we meant to say by "the residual circulation (not shown) and thus ozone (Fig. 3b) in the tropical lower stratosphere is almost brought back to pre-industrial levels". However, the Brewer-Dobson circulation does not slow down relative to pre-industrial levels in our simulations, i.e. it is effectively reset by the solar dimming.

- P8, L21: “As discussed in section 1, tropospheric ozone...affecting human health and air quality”

Done.

- P8, L31: The photolysis reaction has a temperature dependence too (vibrational excitation), which further complicates things.

Yes, there is also a cross section temperature dependence for wavelengths longer than about 300nm, both of which are included in the photolysis scheme. The offsets are rather small and likely not as significant as the changes in UV fluxes and humidity. In any case they are indeed included in the reaction fluxes now given in the revised manuscript (see next question).

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- P9, L13-22: Do you have tropospheric ozone budget data to help with this analysis?

We have added reaction fluxes for the two discussed reactions to our manuscript.

- P9, L24: “in G1, as shown by the data in Table 2.” (A comma and then “see X” does not read well – there are other examples that could be addressed.)

Thank you, we replaced such forms in this and any other occasion where we found this possible.

- P10, L3-14: I would remind the reader that the conclusions are based on simulations with PI conditions. Some of the impacts (ΔT, Δhumidty) will be important for trop chem in general.

We have added the sentences

"Here, we assume pre-industrial conditions by following the G1 scenario, which only allows for low, natural background pollution. Under different forcing scenarios other aspects of tropospheric chemistry could change the surface ozone response."

to our discussion in section 3.4 in the revised manuscript. We have also added the sentences

"Nevertheless, changes in humidity and photolysis as described here are robust modelling features that could occur under a range of geoengineering scenarios and these changes would impact tropospheric chemistry. These mechanisms will be key to tropospheric chemistry considerations under geoengineering in general."

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later in the same section.

- P11, L16-19: You might be able to use data in Madronich (2007) to estimate the impact on vitamin D (he has empirical values for ozone/weighted-UV derived for lots of different action spectra). ...However, if the simulations have PI ODS levels, is it really worth talking up the health impacts too much?

We agree and really just calculate the UVI to illustrate the well-known point about unforeseen consequences. We would thus prefer to stick to the UVI-index calculations already made, mainly because the empirical formula used for the cloud UV changes is also designed to yield the UVI. This way, we are able to compare the results directly.

- P14, L3: I would emphasize this weakness first. It's not terminal, but it is important. [You might be able to point to other studies that have investigated UV-tropospheric chemistry links to infer potential impacts if the ozone precursors were not at PI levels]

We have moved this point to the top of the paragraph and reference other studies (Young et al., 2013 and Squire et al., 2015), which have looked at such effects.

Interactive comment on Atmos. Chem. Phys. Discuss., 15, 31973, 2015.