Answers to reviewer 2 on the ACPD paper (acp-2015-256)

What is the limit of stratospheric sulfur climate engineering?

Ulrike Niemeier and Claudia Timmreck
Max Planck Institute for Meteorology, Bundesstr. 53, 20146 Hamburg, Germany

We thank all reviewers for the careful reading and the thoroughly suggestions. They help us to improve many parts of the paper, especially the comparison to previous studies. Two reviewers were asking on putting more emphasis onto the injection height. We performed two additional simulations with an increased injection height (24 km) and two different meridional extensions (grid box and 30N to 30S). Efficiency is increased by 50% and 36% in these simulations. This allowed a much better comparison to the results of English et al (2012) and Pierce et al (2010) and helped to explain the differences (Fig. 1). We added an extra sub-section for this topic, added the two simulations to table 2 and changed the text in the comparison to other model accordingly. Our main conclusion there is: From Geo10-high and Geo10-30-high can we see that the main impact on efficiency is the increase in injection height, while the increase of the area in meridional directions decreases the efficiency. We assume this also be valid for the difference between "NARROW" and "BROAD" in E12.

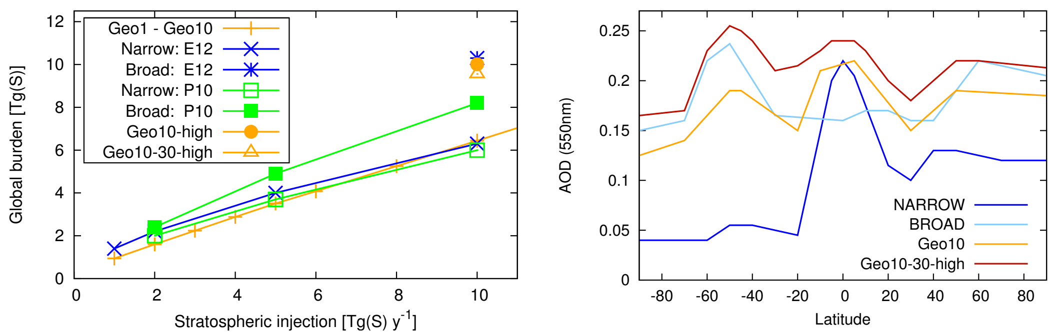

Figure 1: Left: The global sulfate aerosol burden for ECHAM5-HAM simulations Geo1 to Geo10 compared with results from Pierce et al. (2010), P10, and English et al. (2012), E12, for two different emission areas: NARROW, 5 N to 5 S, and BROAD, 30 N to 30 S. In the BROAD simulation the injection area is additionally increased vertically to 20 – 24 km. Right: Plots comparing the zonal mean of the AOD for a narrow and a broad injection area. Plots were created using smoothed values of Geo10 and Geo10-30-high and estimated from "SO_2 NARROW" and "SO_2 BROAD" data after English et al. (2012).

We completely rewrote section 4 and changed the headline to: Limit, uncertainties, and consequences of strong sulfur injections? We included a short discussion of the uncertainties estimated from the experiment design and the model concept. We also include a discussion on some possible impacts: 'What would be the consequences of a 5.5 $W\,m^{-2}$ reduction of the forcing´´ and discuss briefly impacts on precipitation, ozone, cloud condensation particles, which were estimated from previous studies.

General Comments

I find the title somewhat misleading. The paper deals with climate engineering b y injection of SO2 only. Other methods have been explored to inject sulfur (e.g. H2SO4 by Pierce et al., 2010; and OCS injection) which are not dealt with here, and these could be expected to have different efficiencies and limits. A more appropriate title might be 'What is the limit of climate engineering by stratospheric injection of SO2?'

Thanks for this suggestion for a more precise title. We adopted the suggestion.

This paper represents a contribution to the literature on geoengineering by solar radiation management. However, the main conclusion is not new or surprising. That geoengineering injections become less efficient with increasing emissions has been demonstrated and discussed previously by Heckendorn et al. (2009), English et al. (2012) and Pierce et al. (2010).

This was not meant to be the main conclusion of this paper. This conclusion from previous publications raised the question what happens if we want to counterbalance RCP8.5 forcings? Would this be possible or not, as efficiency decreases. We write in the introduction: With increasing injection rate the forcing efficiency, the ratio of sulfate aerosol forcing to injection rate, decreases Heckendorn et al. (2009). This decrease in forcing efficiency is non-linear and the injected SO2 amount needed to reduce strong GHG forcings will be high. This raised the discussion if it will be possible to counteract strong GHG forcing, like RCP8.5, down to e.g. to a level anticipated for 2020 or not. We try, therefore, to estimate a theoretical upper limit for possible SO2 injections after which a further increase in injection rate causes only a negligible decrease in radiative forcing.

This paper does look at sensitivity to injection region both longitudinally and meridionally, which has been discussed in much less detail by previous authors. It also attempts to derive an upper limit for TOA radiative forcing that could be achieved by SO2 injection, though the uncertainty in this number is large and its utility questionable. And it is the first paper to include radiative feedback in the calculation of aerosol distributions as part of the sensitivity calculations.

We performed two additional simulations with an increased injection height (24 km) and two different meridional extensions (grid box and 30N to 30S) to further complete this study.

The authors treat the subject of geoengineering by solar radiation management as if there is only one possible method (injection of SO2) and if employed, it would be used to halt future global warming. A more thorough discussion would mention other methods, such as injection of H2SO4 or solid particles, e.g. soot or TiO2. It should also be mentioned that amounts of geoengineering which slow, rather than attempt to halt, surface temperature rise, may have a role in an effective climate strategy (see e.g. MacMartin et al., 2014).

We added a paragraph on other methods to the conclusions: Similar to the injection of SO2 also aerosols could be injected. Ferraro and Charlton-Oerez (2011) studied the impact of limestone, Titania and soot. Soot has a large green house effect, which reduced its efficiency and the simulated forcing of Titania showed strong dependencies on the particle size, with even positive forcing. Following Weisenstein and Keith (2015) any solid aerosol introduced into the stratosphere would grow via coagulation and accumulation with the consequence of large uncertainties on simulated results. Alternative SRM designs like regional implementation Haywood et al. (2013) or reducing only the rate of temperature increase MacMartin et al. (2015) would require different amounts of SO2 injection in an RCP8.5 scenario.

The fact that the very high levels of geoengineering discussed in this paper would almost certainly present unacceptable risks to ozone gets one brief mention at the end of Section 4. This important point should be included in the introduction as well, and could include an editorial comment that RCP8.5, with continued growth in use of fossil fuels, is extremely undesirable and has no easy fix via geoengineering injection of SO2.

We added some published estimations on ozone impact to the text. The values are very uncertain as all previous studies deal with much smaller amounts of sulfate:Previous geoengineering studies including ozone chemistry estimated changes over the polar region of -10% for an injection of 2 Tg(S)/y (Tilmes et al. (2008)) and around -5% in a multimodel ensemble for 4 to 6 Tg(S)/y (Pitari et al. (2013)). Both studies show a slight increase in the ozone concentration over the Tropics. The impact of higher injection rates might be estimated from volcanic eruptions. Randel et al. (1995) show a decrease of -10% over high latitudes and $\pm$2% over Tropics from satellite measurements after the Mt.Pinatubo eruption, similar to Aquila et al. (2014). These values seem to be similar to the ones from geoengineering studies. For stronger injection rates only super volcano studies cab be taken as reference. Timmreck and Graf (2006) calculated height dependent changes of $+$ 100% and $-$ 25% in the tropics for a Yellowstone eruption of 850 Tg(S). Bekki et al. (1996) calculated for a simulation of the Toba eruption (about 3000 Tg(S)) a decrease of 40% over the poles and -60% to +150% over the Tropics.

The paper's methodology is sound and generally well documented, with a few exceptions noted under specific comments. The language could use some tweaks to improve the English usage, as noted under 'technical corrections'. In places the discussion could be broadened and I suggest three references to be added. I support publication after the issues detailed here are addressed.

Specific Comments

Page 10941, line 16, and also in Abstract 'These previous studies were performed with SO2 injections of 1 to 10 Tg(S)/yr ' Pierce et al. (2010) show SO2 injections up to 20 MtS/yr.

We revised this to up to 20 MtS/yr.

Page 10943, line 7 'Nucleation was adapted to high SO2 concentrations...' Do you mean high H2SO4 concentrations? SO2 plays no direct role in nucleation.

We changed this in the text.

Page 10945, lines 24-25' These data are derived from a double radiation call' Please explain 'double radiation call'

We changed the text to: These data are derived from calling the radiation calculation in the model twice, once without and once with aerosols, whereby only the latter is seen from the climate model.. With this method we are able to calculate the instantaneous aerosol forcing only and get the radiative forcing of the aerosol.

Page 10951, line 23: The statement that 'the aerosol is coupled to a radiation scheme' in the Pierce et al. (2010) work is misleading. That study and the Heckendorn et al. (2009) study calculated changes in radiation due to aerosols but there was no feedback of radiation into the aerosol distribution. Aerosols were calculated in a 2-D model with fixed circulation off-line from radiative effects.

We took this into account and changed the formulation in the text.

Page 10953-10954, the paragraph spanning this page transition Robock (2009) did not perform a serious analysis of delivery systems for geoengineering. The work of McClellan et al. (2012) covers this topic in more depth and would provide a more appropriate citation. Table 1 of that reference gives number of aircraft required to lift 1 Mt-S per year into the stratosphere for several existing aircraft types. From this, the fleet size required to inject 26 or 45 Tg-S/yr can be estimated.

We rewrote the section and skipped, related to other reviewers comments, the discussion on a necessary amount of flights. But we used the McClellan et al. (2012) paper for citing the possible flight height.

Page 10954, lines 16 - 17 In the discussion of possible cloud feedback, add reference to Cirisan et al. (2013). The reference indicates that this feedback might go either way. I suggest changing 'would' to 'might': 'the resultant brighter clouds might reflect more sunlight, a positive feedback' You might consider replacing 'R TOA'with 'ΔR TOA' to be clear that you are talking about the change in top-of-atmosphere radiative forcing due to geoengineering aerosols, not total radiative forcing.

We use ΔR TOA now and changed the text on cloud feedback to: The resultant brighter clouds might reflect more sunlight, a positive feedback. Cirisan et al (2013) describe the mid-latitudinal averages in the range of $\pm$ 0.04 W m^{-2} for injection rates up to 5 Tg(S) yr^{-1}. Locally this values can be larger but the global impact can be assumed as small also for larger injection rates. Furthermore Kuebbeler et al. (2012) showed that a vertical shift of the tropopause height caused by the warmer lower stratosphere has implications on cirrus clouds and the cloud top height, with further impacts on the hydrological cycle.

We included the technical correction in the text. Thank you very much for the careful reading and the suggestions.

References

Aquila, V., Garfinkel, C. I., Newman, P., Oman, L. D., and Waugh, D. W.: Modifications of the quasi-biennial oscillation by a geoengineering perturbation of the stratospheric aerosol layer, Geophys. Res. Lett., 41, 1738–1744, doi:10.1002/2013GL058818, 2014.

Bekki, S., Pyle, J. A., Zhong, W., Haigh, R. T. J. D., and Pyle, D. M.: The role of microphysical and chemical processes in prolonging the climate forcing of the Toba eruption, Geophys. Res. Lett., 23, 2669–2672, 1996.

Cirisan, A., Spichtinger, P., Luo, B. P., Weisenstein, D. K., Wernli, H., Lohmann, U., and Peter, T.: Microphysical and radiative changes in cirrus clouds by geoengineering the stratosphere,, J. Geophys. Res. Atmos., 118, 4533–4548, doi:10.1002/jgrd.50388, 2013.

English, J. M., Toon, O. B., and Mills, M. J.: Microphysical simulations of sulfur burdens from stratospheric sulfur geoengineering, Atmos. Chem. Phys., 12, 4775–4793, doi: 10.5194/acp-12-4775-2012, 2012.

Ferraro, A. J. a. E. H. and Charlton-Oerez, A.: Stratospheric heating by potential geoengineering aerosols, Geophys. Res. Lett., 38, L24 706, doi:10.1029/2011GL049761, 2011.

Haywood, J., Jones, A., Bellouin, N., and Stephenson, D.: Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall, Nature Climate Change, 3, 660–665, doi: 10.1038/nclimate1857, 2013.

Heckendorn, P., Weisenstein, D., Fueglistaler, S., Luo, B. P., Rozanov, E., Schraner, M., Thomason, L. W., and Peter, T.: The impact of geoengineering aerosols on stratospheric temperature and ozone, Environ. Res. Lett., 4, 045 108, doi:10.1088/1748-9326/4/4/045108, 2009.

Kuebbeler, M., Lohmann, U., and Feichter, J.: Effects of stratopheric sulfate aerosol geo-engineering on cirrus clouds, Geophys. Res. Lett., 39, L23 803, doi: 10.1029/2012GL053797, 2012.

MacMartin, D., Caldeira, K., and Keith, D.: Solar geoengineering to limit the rate of temperature change, Phil. Trans. R. Soc. A, 372, 20140 134, doi:10.1098/rsta.2014.0134, 2015.

McClellan, J., Keith, D. W., and Apt, J.: Cost analysis of stratospheric albedo modification delivery systems, Environmental Research Letters, 7(3), doi:10.1088/748-9326/7/3/034019, 2012.

Pierce, J. R., Weisenstein, D. K., Heckendorn, P., Peter, T., and Keith, D. W.: Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft, GRL, 37, L18 805, doi:10.1029/2010GL043975, 2010.

Pitari, G., Aquila, V., Kravitz, B., Robock, A., Watanabe, S., Luca, N. D., Genova, G. D., Mancini, E., Tilmes, S., and Cionni, I.: Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP), Journal of Geophysical Research, 119, 2629–2653, doi:10.1002/2013JD020566, 2013.

Randel, W. J., Wu, F., III, J. M. R., Waters, J. W., and Froidevaux, L.: Ozone and temperature changes in the stratosphere following the eruption of Mount Pinatubo, J. Geophys. Res., 100(D8), 16 753–16 764, doi:10.1029/95JD01001, 1995.

Tilmes, S., Müller, R., and Salawitch, R.: The sensitivity of polar ozone depletion to proposed geoengineering schemes, Science, 320(5880), 1201–1204, doi: 10.1126/science.1153966, 2008.

Timmreck, C. and Graf, H.-F.: The initial dispersal and radiative forcing of a Northern Hemisphere mid–latitude super volcano: A model study, Atmos. Chem. Phys., 6, 35–49, URL http://www.atmos-chem-phys.net/6/35/2006/, 2006.

Weisenstein, D. K. and Keith, D.: Solar geoengineering using solid aerosol in the stratosphere, Atmos. Chem. Phys. Discuss., 15, 11 799–11 851, doi:10.5194/acpd-15-11799-2015, 2015.