Upper tropospheric ice sensitivity to sulfate geoengineering

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Abstract

In light of the Paris Agreement which aims to keep global warming under 2 C in the next century and considering the emission scenarios produced by the IPCC for the same time span, it is likely that to remain below that threshold some kind of geoengineering technique will have to be deployed. Amongst the different methods, the injection of sulfur into the stratosphere has received much attention considering its effectiveness and affordability. Aside from the rather well established surface cooling sulfate geoengineering (SG) would produce, the investigation on possible side-effects of this method is still ongoing. For instance, several recent studies have investigated the effect SG would have on upper tropospheric cirrus clouds, expecially on the homogenous freezing mechanisms that produces the ice particles [2]. The goal of the present study is to better understand the effect of thermal and dynamical anomalies caused by sulfate geoengineering on homogeneous formation of ice crystals by comparing a complete SG simulation with a RCP4.5 reference case and with a number of sensitivity studies where atmospheric temperature changes in the upper tropospheric region are specified in a schematic way as a function of the aerosol driven stratospheric warming and mid-lower tropospheric cooling. Surface cooling and lower stratospheric warming increase atmospheric stabilization, thus decreasing updraft and with it the amount of water vapor available on formation of ice crystals through homogeneous freezing in the troposphere. However, what still needs to be investigated is the interaction between this dynamical effect and the tropospheric cooling (which would increase ice nucleation rates) and the stratospheric warming (which would reflect in a warming of the uppermost troposphere, thus reducing ice nucleation rates), in order to understand how these effects combine together. This is important because cirrus ice clouds scatter incoming shortwave and absorb outgoing infrared radiation, but the longwave absorption dominates, so a decrease in coverage would produce a negative radiative forcing. This would go in the same direction as the direct effect of incoming radiation scattering by the sulfate aerosol, thus influencing the amount of sulfur needed to counteract the positive RF increase due to future increases in greenhouse gases.

Introduction

Several studies have proposed mechanisms by which SG would affect upper-tropospheric cirrus clouds, reaching, however, contradictory conclusions. Cirisan et al. [1] found that SG directly provides ice nuclei (IN) of a larger size with respect to those in the unperturbed atmosphere, resulting in a rather small increase in cirrus cloud coverage. Kuebbeler et al. [2], on the other hand, found that SG would decrease cirrus cloud coverage because of changes in temperature, vertical velocity and water vapor updraft.

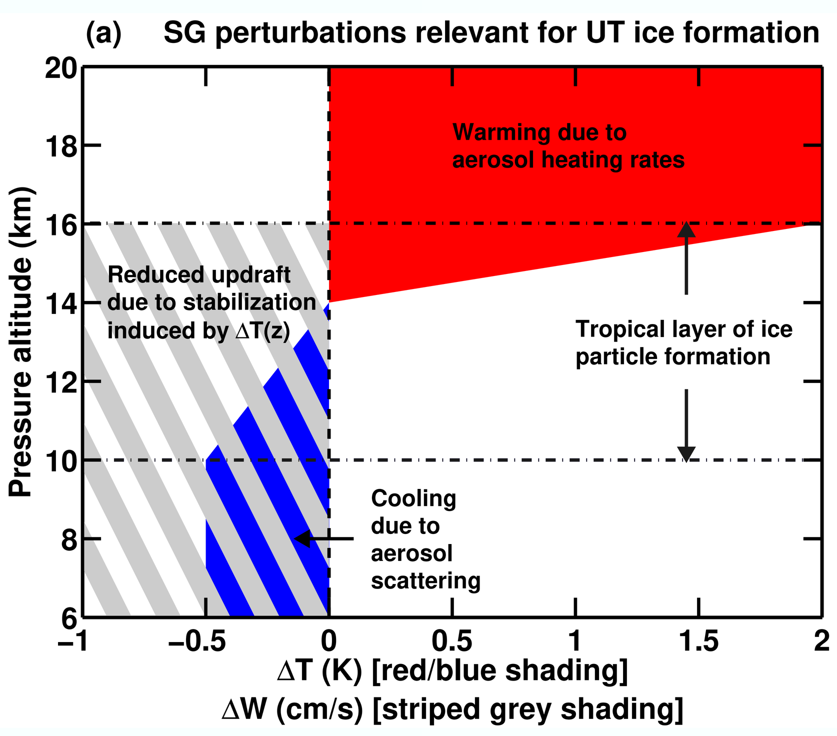

Figure 1: Scheme of SG effect on homogeneous freezing

The aerosol driven surface cooling, coupled with the lower-stratospheric warming, stabilises the atmosphere due to a decreased vertical temperature gradient, thus reducing the available turbulent kinetic energy and the vertical updraft. This results in a decrease of the upper-tropospheric ice crystal formation, which in turn produces a less efficient trapping of the planetary longwave radiation and a reduction of the net atmospheric greenhouse effect. Figure 1 presents a compact summary of the dynamical perturbations induced by SG and relevant for the ice particle formation via homogeneous freezing. Lower vertical velocities force a decrease in ice crystal number concentration due to the decreasing water vapor transport from below, with consequent lower supersaturation. The temperature dependence is inverse, because lower temperatures allow for more ice crystals, due to the slower depositional growth and the higher nucleation rate [3].

Experiment setup

Three geoengineering simulations have been designed, to be compared against a background simulation (using anthropogenic forcing from RCP4.5) for the 2030-2069 period, using the ULAQ-CCM model. The main simulation **G4** considers of a 8 Tg SO_2/yr injection starting from 2020; since the ULAQ-CCM is not an atmosphere-ocean coupled model, it uses prescribed SSTs from a simulation using the same sulfate injection run by the CCSM-CAM4 model in order to account for oceanic response to SG. Together with the G4 simulation, two sensitivity cases have been run. **G4sen1**, uses the same dynamics from the G4 simulation, but uses RCP4.5 temperatures for all calculations regarding homogeneous freezing in the tropospheric layers. **G4sen2** replicates the simulation by Kuebbeler et al. [2] by using a G4 simulation with prescribed SSTs temperature from RCP4.5. This is done in order to highlight the temperature dependance for cirrus ice formation, given a certain vertical velocity change. Figure 2 shows the differences in temperature and updraft in G4 and G4sen2 with respect to RCP4.5. In G4 we observe a tropospheric cooling of $\simeq$ 1-2K in the ice formation region throughout all latitudes, while the warming due to sulfate aerosol absorption in the shortwave is confined above the tropopause. Vertical velocity, which results almost completely from synoptic scale motion and gravity waves, is calculated as a function of the turbulent kinetic energy. It is reduced expecially in the tropical region by $\simeq$ 1-2 cm/s ($\simeq$ 10 % of the total w) due to the atmospheric stabilization caused by the reduction in the temperature gradient.

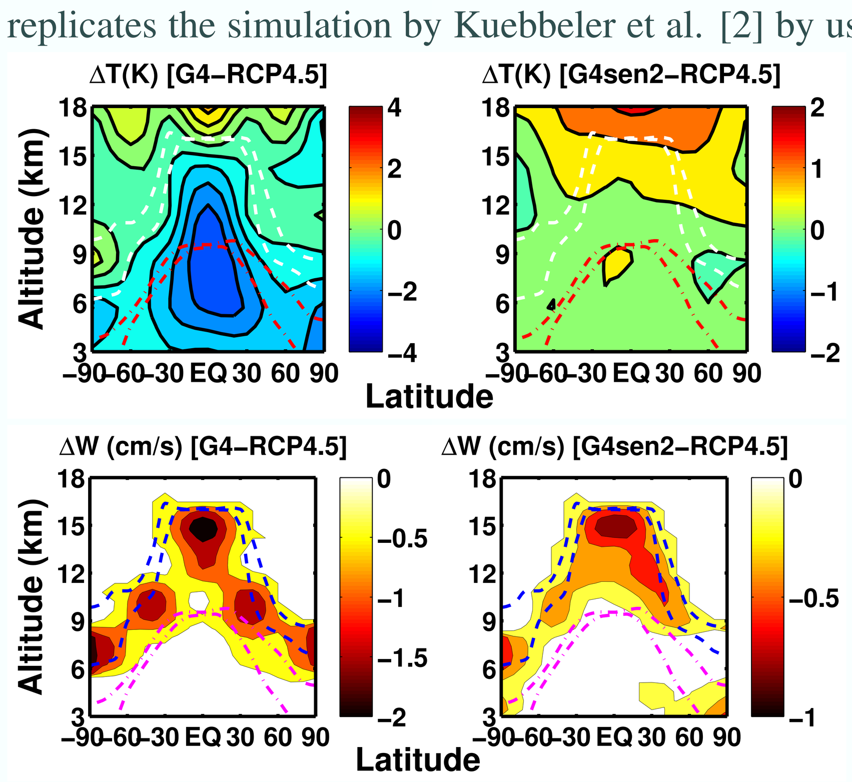

Figure 2: Temperature and W changes in the four experiments. The dashed line show the mean tropopause height $\pm1\sigma$. The dash-dotted line show the mean height at which the temperature reaches 238K, thus enabling homogeneous freezing.

Effects on ice crystals size and number density

Extinction due to sub-visible ice particles is calculated as $2\pi r^2 n$, where r and n are radius and number density of the ice particles respectively, meaning that the optical thickness depends on how the population and the size of ice particles responds to temperature and updraft changes.

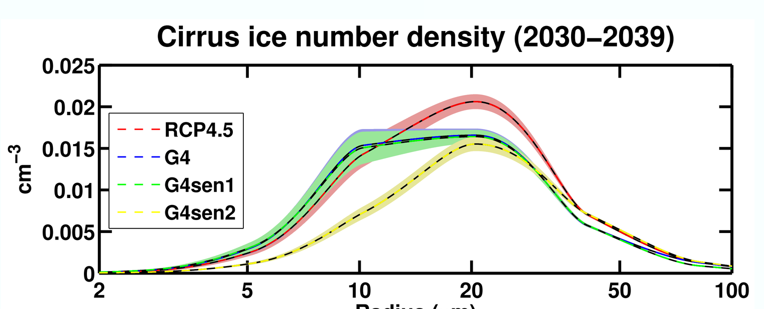

Figure 3: Number density of ice particles with respect to the radius averaged over all latitudes.Whenever shades of the same colour are present, they represent $\pm1\sigma$ for the ensemble over the 10 year period.

Figure 3 shows the differences in size distribution in the different experiments. Already from this we can see how the shapes of the curves are very similar for the G4 and G4sen1 cases, where the dynamical driver is the same and only temperature changes. Together with that, figure 4 shows that while the average effective radius remains of the same order of magnitude for all four cases, most changes in the different experiments happen in the average ice particles number density, with the value being reduced by $\simeq$ 10% for G4 and G4sen2 and by more than 20% for G4sen2. When these two effects are taken into account in the optical depth calculations, we obtain significant changes at mid-to-higher latitudes in all three SG experiments, with high similarities between G4 and G4sen1 and values for G4sen2 much more similar to the ones in RCP4.5.

In general the same decrease in optical depth found in [2] is present for G4sen2, while the G4 case produces a further decrease in optical depth even though tropospheric temperatures are cooler. The effects regarding temperature and updraft cannot be easily separated, however by comparing similar simulations some observations can be made. G4 and G4sen1 have the exact same dynamics, but G4sen1 has warmer temperatures. This further reduces the size of the particles, producing another 10% decrease in optical depth.

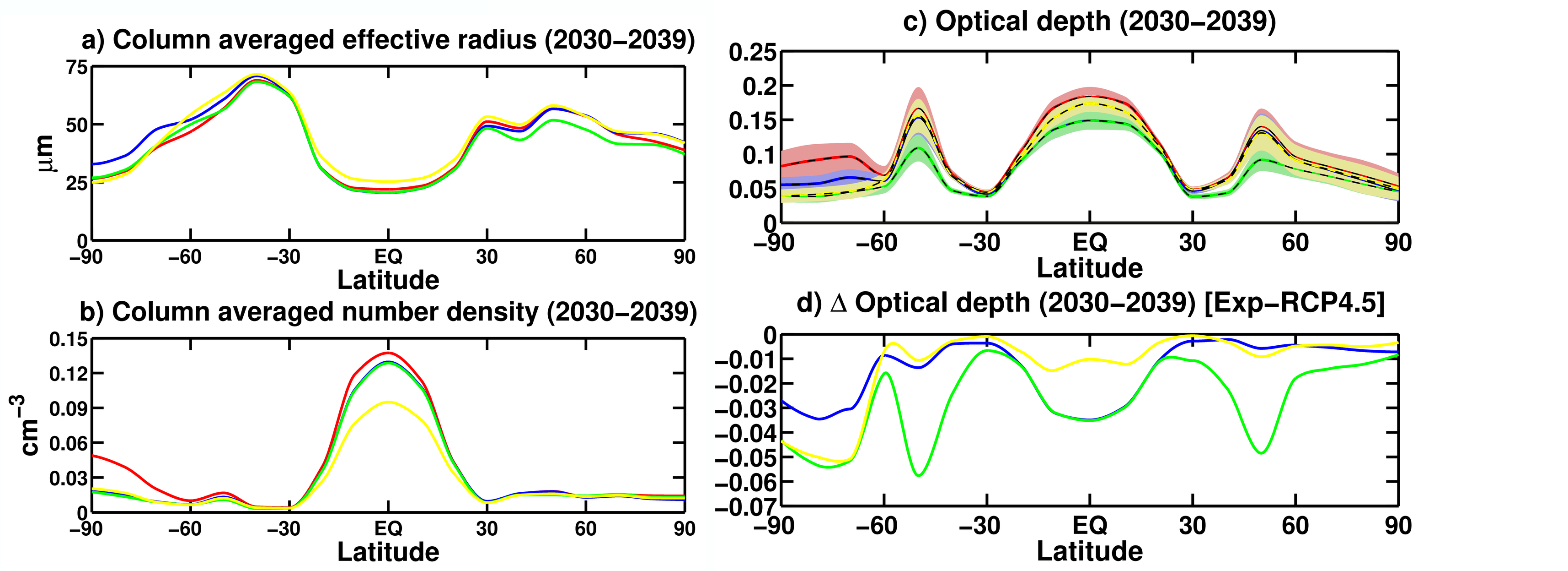

Figure 4: a) Effective radius, b) number density c) optical depth and ed) differences in optical depth with respect to RCP4.5 over the different latitudes.

Consequences on radiative forcing

Experiment	Ice OD	Δ RF SW	Δ RF LW	Δ RF net
RCP4.5	0.112	-	-	-
G4	0.098	0.14	-1.05	-0.90
G4sen1	0.087	0.13	-1.68	-1.55
G4sen2	0.104	0.13	-0.65	-0.51

Δ SO_4 AOD	Δ RF SW	Δ RF LW	Δ RF net
0.076	-1.76	0.91	-1.13

Table 1: On the left, globally averaged values for tropospheric ice optical depth and differences in RF (in W/m^2) between the SG experiments and the RCP4.5 case due to changes in ice crystal concentration and size. On the right, differences in aerosol optical depth due to a 8 Tg-SO_2/yr injection and its effect on RF (in W/m^2). These values are unchanged between the three SG simulations. All results are for All Sky conditions.

Top of the atmosphere radiative forcing calculations allow us to estimate the effect of these decrease in ice crystal on the Earth's climate. For all cases, with respect to the RCP4.5 scenario, we obtain a small increase in SW RF, because of the decreased scattering of incoming solar radiation by the ice particles. However, such an effect is largely covered by the decrease in LW RF due to a lessened capacity of the ice particles to trap outgoing planetary radiation, therefore the obtained net effect on RF is negative, and as can be seen in Figure 5 and Table 1 such a negative effect is of the same order of magnitude of the negative RF due to increased scattering by stratospheric sulfate particles.

For G4sen2 we obtain a RF very similar to the one in [2], while G4 shows a 80 % increase in negative forcing with respect to G4sen2.

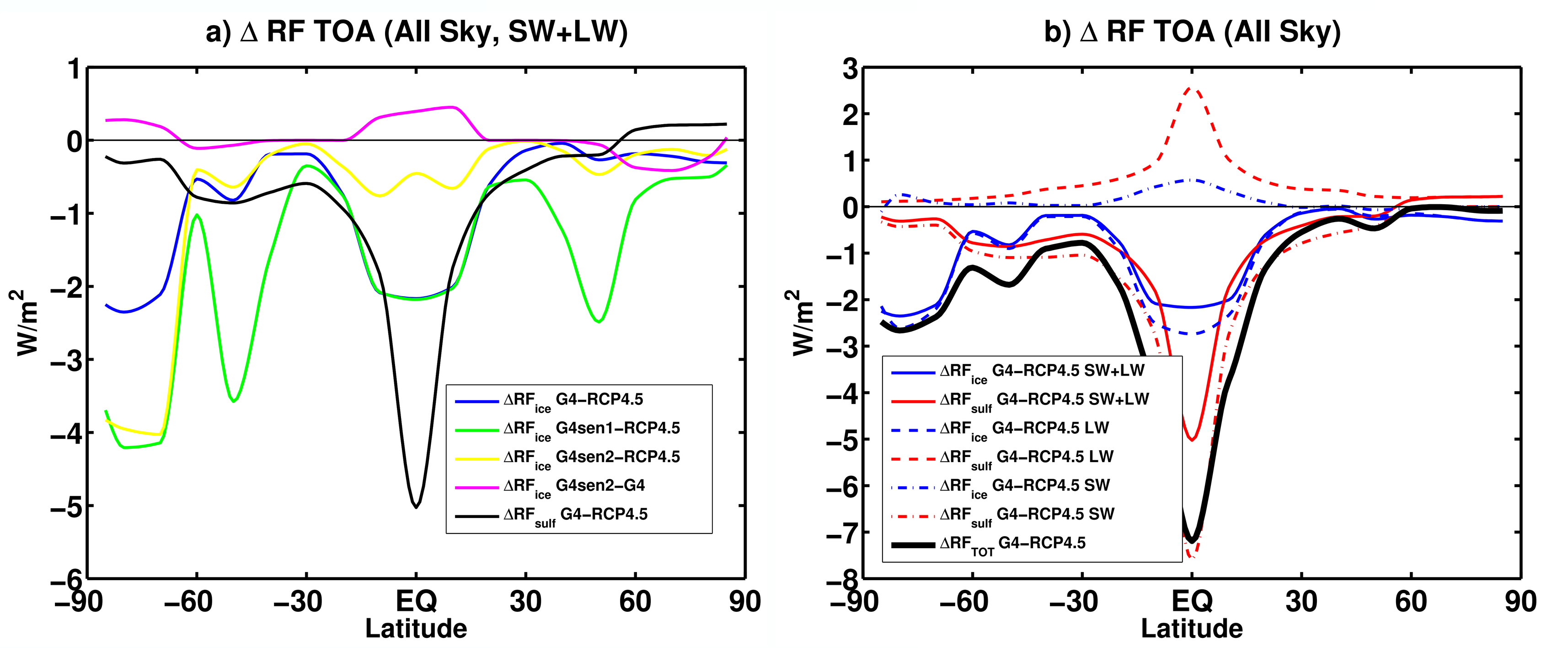

Figure 5: a) Latitudinal distribution of net RF differences between experiments. b) Breakdown of SW and LW contribution to RF over latitudes in the G4 experiment for both ice contribution (blue lines) and sulfate (red lines).

Conclusions

- In the conclusion of [2], the authors state that it would be important to "redo the simulations with a mixed layer ocean (MLO) in order to allow the ocean to respond to applied forcing". Comparing the simulation with varying SSTs with the one with fixed SSTs, we observe a further decrease in vertical velocities and a cooling of tropospheric temperatures.
- When comparing the effects that this thermodynamical anomalies have on ice crystal formation with respect to a reference scenario, we obtain an even smaller optical depth in the G4 case, meaning that the further decrease in vertical velocities is not balanced by the cooling of the troposphere. In turn this produces a larger negative forcing due to ice crystals. This highlights the importance of running SG experiments taking into account the aerosol feedback on surface temperatures, since the increased atmospheric stabilization has meaningful feedbacks on the dynamics of the planetary system.
- In both cases, a negative RF occurs due to the reduction in the ice crystal population, and this negative RF is of the same order of magnitude as the negative RF due to increased scattering caused by the sulfate aerosol injection. This might mean that, when effects on ice crystal are taken into account, any possible SG experiment could require less SO_2 injection then previously expected in order to cool the planet.

References

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