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Project title: **"Implications and Risks of Engineering Solar Radiation to Limit Climate Change (IMPLICC)"**

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1 General remarks

The analysis of simulations on the impact of climate engineering (CE) techniques on the climate started in the EU Project IMPLICC (ended Sept 2012) and is currently being continued within the project CELARIT of the SPP (1689) of the German Science Foundation that runs in the second phase until summer 2018. Simulations for this project have been performed under project account bm0550, while data processing and storage was mostly done within the data project bm0695. Therefore, this report combines both projects.

2 Scientific accomplishments

The overall goal of the project is to significantly increase the level of knowledge about the feasibility and implications of climate engineering (CE) options. Among these possibilities, a deliberate manipulation of the radiative budget of the Earth may allow a counterbalancing of the effects of continued greenhouse gas emissions on global temperature, but may also result in undesirable side effects. A complex climate model and a model which includes aerosol microphysics are used to quantify the effectiveness and side effects of such CE concepts. One of the assumed techniques, the injection of sulfur into the stratosphere of sulfate aerosol manipulation (SAM), requires detailed knowledge about the microphysical evolution of sulfur and the transport and distribution of the particle (Niemeier and Tilmes, 2017).

Evolution and transport of the sulfur determines the effectivity of the injection. The top of the atmosphere forcing of sulfate depends on the particle size as scattering of solar radiation decreases with increasing particle size. Increasing the injection rate increases the particle size, which leads to a discussion of a upper limit of SAM (Niemeier and Timmreck, 2015). Niemeier and Schmidt (2017) added another component to this study: the number of model levels was increased to 90, which allows the simulation of the quasi biennial oscillation (QBO). These studies were performed with a middle atmosphere version of the General Circulation Model (GCM) ECHAM5 that is interactively coupled to a modified version of the aerosol microphysical model HAM.

2.1 Injection of sulfate into the stratosphere – impact on stratospheric dynamics and consequences for radiative forcing

The injection of sulfur warms the lower stratosphere. This accelerates tropical up welling, which inhibits the downward propagation of zonal momentum. Additionally, the warming disturbs the thermal wind balance and prolongs the phases of westerly winds in the lower stratosphere. Simulations with ECHAM5-HAM show that an injection of 4 Mt(S)/y at 60 hPa causes a prolongation of the westerly phase in the lower stratosphere. Increasing the injection rate further has the consequence of a complete shut down of the oscillation. In the lower stratosphere, between 50 hPa and 25 hPa a layer with constant westerly winds develops, accompanied by a layer of constant easterly winds above (Niemeier and Schmidt, 2017).

The transport of chemical species and aerosols out of the tropics depends on the phases of the QBO. A westerly jet in the lower stratosphere increases the tropical confinement of the sulfate particles and reduces meridional transport to the poles. The consequences are twofold: within the tropics the particles grow larger, reducing scattering, and the aerosol optical depth in the extra tropics is reduced due to less

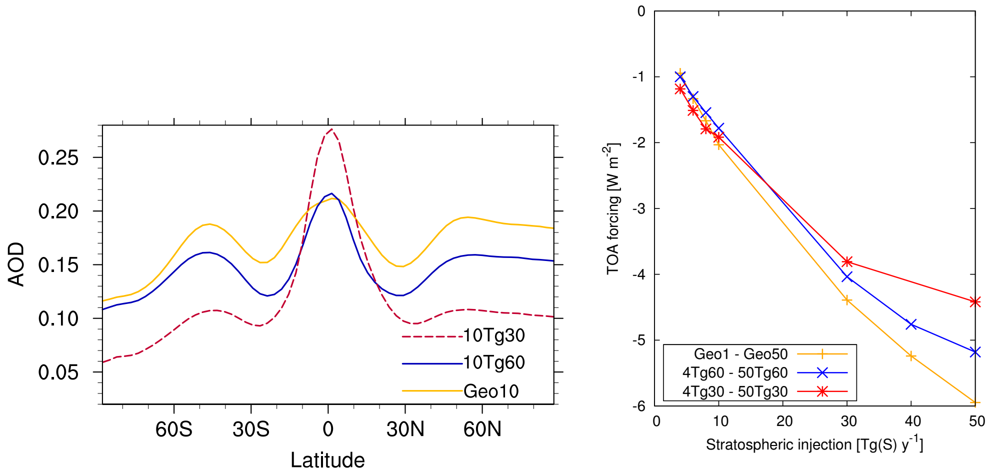

Figure 1: Left: Zonal mean of sulfate aerosol optical depth for an experiment without generated QBO (Geo10), with generated QBO (10Tg60), both with injections at a height of 60 hPa, and with generated QBO but injected at 30 hPa (10Tg30). All three simulation were performed with with an injection rate of 10 Tg(S) yr^{-1}. Right: Top of the atmosphere radiative forcing against injection rate for the same experiments and, additionally, varying injection rate.

and larger particles in this region (Fig. 1, left). Both has impact on the global top of the atmosphere (TOA) forcing caused by the sulfate and, thus, the effectivity of SAM (Fig. 1, right).

In the extra tropics the AOD is roughly 20% lower in simulation 10Tg60 (with generated QBO) compared to Geo10 (without generated QBO). The better representation of the stratospheric dynamics in the higher resolution simulations and the resulting stronger confinement of the particles in the tropics cause them to grow larger which reduces scattering and, thus, the AOD. Increasing the injection height to 30 hPa, simulation 10Tg30, further intensifies the equatorial confinement. Thus, injection at 30 hPa results in strong tropical maxima of the AOD.

Comparison of the global TOA forcing (Figure 1, left) of sulfate of XTg60 (with generated QBO) to simulations with lower vertical resolution (GeoX, orange line) of Niemeier and Timmreck (2015) indicates a smaller increase with increasing injection rate in the XTg60 simulations. Thus, the efficiency of the sulfur injection with increasing injection rate decreases stronger than described in Niemeier and Timmreck (2015). While forcings are very similar for lower emission rates, for injection rates above 10 Tg(S) yr^{-1} the forcing in the XTg60 simulations is about 10% lower. Previous studies showed an increasing efficiency with increasing injection height. In Niemeier and Timmreck (2015) TOA forcing increases by 50% for an injection of 10 Tg(S) yr^{-1} when changing the injection height from 60 hPa to 30 hPa. In this study, TOA forcing increases only by 8% for 10Tg30 compared to 10Tg60. The efficiency even decreases for strong injection rates of 20 Tg(S) yr^{-1} and more as a consequence of the strong tropical confinement in the high injection cases.

Finally, it needs to be stated that the simulated impact of stratospheric sulfate heating on the QBO is only a model result, which cannot be evaluated in reality. However, our simulations show that the efficiency of sulfur injections may depend crucially on the jet structure in the tropical stratosphere, which itself will be influenced strongly by the injections, and that the dynamical effects vary strongly even in different configurations of the same model. To reduce this uncertainty a better understanding of tropical dynamics and model simulations without the necessity of gravity wave parameterizations, i.e. with horizontal resolutions at least one order of magnitude higher than used here, may be necessary.

References

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