Projektaccount: **550** und **695**, Berichtszeitraum: **1.1.2014 - 31.12.2015**

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 CEIBRAL of the SPP (1689) of the German Science Foundation that runs in the first phase until September 2016. 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 aiming at a reduction of the incoming solar radiation.

For a better comparability of the results the "Geoengineering Model Intercomparison Project" (GeoMIP) (Kravitz et al, 2011) has been formed and several experiments were performed with the MPI-ESM at DKRZ. One of the assumed techniques, the injection of sulfur into the stratosphere, requires detailed knowledge on the microphysical evolution sulfur, the formation of sulfate aerosols and the transport and distribution of the particle.

Niemeier and Timmreck raised the question ’What is the limit of climate engineering by stratospheric injection of SO_2?’. The study was motivated by the fact that the efficiency of SO_2 injections decreases with increasing injection rate and the still open question whether it is possible to counterbalance the green house gas (GHG) forcing of an RCP8.5 projection towards year 2020 forcing level or further to preindustrial conditions. Such scenarios are planned for GeoMIP6.

2.1 A limit of SO2 injections?

CE simulations 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. With this model a detailed study of the evolution of the injected $SO2$ was possible (Niemeier and Timmreck, 2015). One focus of the study is on particle size which is a crucial parameter for the effectiveness of stratospheric aerosols as it influences absorption and scattering properties as well as the sedimentation velocity.

ECHAM5-HAM simulations of injection rates up to 100 Tg(S) yr^{-1} were analyzed with respect to the efficiency of the injections followed by a discussion about injection strategies such as modification of the injection area size and different model configurations. Figure 1 (left) shows the simulated change in global radiative fluxes at the top of the atmosphere (TOA) for different SO_2 injection rates. The orange curve shows the data for the TOA forcing (ΔR_{TOA}), net shortwave (SW) plus net longwave (LW) radiation, for the different injection rates. The red curve in Fig. 1 (left) is a fit of ΔR_{TOA} as function of injection rate x (in

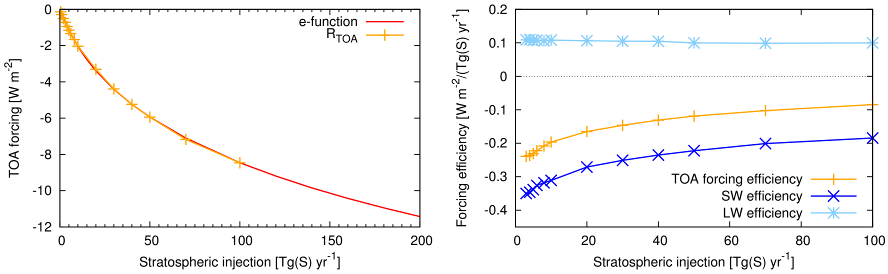

Figure 1: (Left) Top of the atmosphere (TOA) radiative fluxes (net shortwave plus net longwave, orange) for different injection rates and exponential fit of TOA forcing (red). (Right) Forcing efficiency of SO_2 injections expressed in [W m^{-2} (Tg(S) yr^{-1})$^{-1}$], for total radiation (orange), and the SW (dark blue) and LW (light blue) contributions.

Tg(S) yr^{-1}). Following the fit curve, doubling of the injection rate, results in an increase of only 40 % in the forcing.

A more detailed illustration of the radiative forcing efficiency at TOA is given in Fig. 1 (right), where the ΔR_{TOA} is split in SW and LW parts. This figure clearly depicts that the decreasing radiative forcing efficiency results from the SW part. As injection rates increase, particle number and radii increase stronger in coarse mode than in accumulation mode. With increasing particle size scattering becomes less effective. Efficiency of LW radiation at TOA is almost constant and positive at 0.1 W m^{-2} (Tg(S) yr^{-1})$^{-1}$. So the TOA LW flux anomalies are linearly dependent on the injection rate and contribute to the GHG effect instead of counteracting it.

2.2 Injection of sulfate into the stratosphere – impact on stratospheric dynamics

The impact of sulfur emissions on the dynamic of the stratosphere and, as a feedback process, also on the transport of species was determined with ECHAM5-HAM simulations using 90 vertical levels. This high vertical resolution allows the model to develop a quasi-biannual oscillation (QBO) in the tropical stratosphere. Injecting SO_2 into the stratosphere in this model version showed a clear impact on the frequency of the oscillation.

The absorption of long wave radiation by the sulfur aerosol causes a warming of the stratosphere. One consequence is an increased vertical motion in the tropical stratosphere which causes a deceleration of the QBO downward propagation and therefore a prolongation of the QBO west phase of the zonal wind. Injecting 4 Mt S per year the period of the oscillation is prolonged. A further increase of the injection to 8 Mt S/year causes even stronger changes and forces the zonal wind into a permanent west phase in a height between 50 hPa and 25 hPa and above into an east phase. Due to interaction of the QBO with the meridional transport in the stratosphere, the vertical extension of the east jet has consequences for the trace gas distribution and thereby feeds back onto the dynamics of the stratosphere.

2.3 GeoMIP

In the model intercomparison project GeoMIP several CE option have been studied: stratospheric injection of sulfur, marine cloud brightening, increasing the albedo of the ocean. This has led to several papers (24 currently, 17 with participation of the authors of this report). This initiative will continue as part of CMIP6.

References

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GeoMIP: http://climate.envsci.rutgers.edu/GeoMIP

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