Projektaccount: **550** and **695**, Period: **1.1.2018 - 31.12.2018**

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

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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 2019.

1 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 (stratospheric aerosol manipulation, SAM), requires detailed knowledge about the microphysical evolution of sulfur and the transport and distribution of the particle (Niemeier and Tilmes, 2017). The 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.

1.1 Injection of sulfate into the stratosphere – impact on stratospheric dynamics in different models

The impact of SAM on climate and stratospheric dynamics caused by aerosol radiation interactions: scattering of solar radiation and absorption of infrared radiation. The resulting aerosol radiative forcing depends on sulfur evolution: the chemical transformation of sulfur dioxide into the aerosol phase, and the resulting particle size; but also on stratospheric dynamics and sink processes. Niemeier and Timmreck (2015) could show that the efficiency of the injection and, thus, the cooling at the surface, decreases exponentially per injected unit when increasing the injection rate. Increasing the injection rate increases the particle size and larger particles scatter less. Niemeier and Schmidt (2017) used the same model but with 90 levels instead of 47 levels. This allowed to generate a quasi biennial oscillation (QBO) in the tropical stratosphere. The impact of the sulfate heating on the QBO decreased the efficiency given in Niemeier and Timmreck (2015). If changing the amount of vertical levels has such a clear impact, it may not wonder that other models show very different results.

Several results of model inter-comparison projects (GeoMIP, VolMIP, ISA-MIP) show different sulfur evolution pathways and transport which result in a large inter-model spread in the simulated radiative forcing and thus the surface cooling effect. Figure 1 shows in the upper part of the figure the surface temperature response of different IPCC scenarios and the range of different model studies in comparison of the cooling due to SAM from two different models. The uncertainty range in the SAM studies is much larger than in the ICPP scenarios. The related radiative forcing is highly uncertain and varies by almost 4 W m^{-2} when injecting 10 Tg sulfur per year in four different models. In order to better understand the different results, we compare in detail results of ECHAM5-HAM and WACCM (Richter et al, 2017) in a close collaboration with NCAR scientist Simone Tilmes and Yaga Richter.

Niemeier and Schmidt (2017) have shown that the transport of sulfate depends on the phase of the QBO. The heating of the aerosols prolongs the phases of the QBO after an continuous injection and even shuts down the QBO for stronger injections. A westerly phase in the lower stratosphere increases tropical confinement of the aerosols and reduced meridional transport. Therefore, the phase of the QBO impacts also

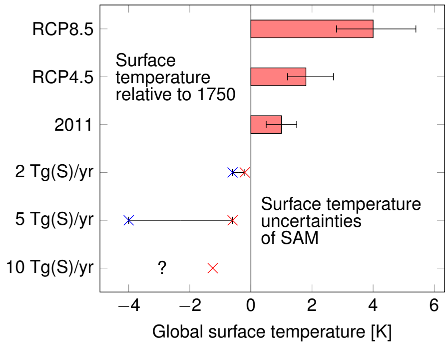

Figure 1: Global near surface temperature estimates for forcings of greenhouse gases of IPCC scenarios and three sulfur injection scenarios. SAM cooling estimates were only available for two Earth system model simulations for injection rates of 2 and 5 $Tg(S)yr^{-1}$ and are almost unknown for $10Tg(S)yr^{-1}$. Red crosses show ECHAM5-HAM results.

the distribution of sulfate after a volcanic eruption.

First results of the comparison of ECHAM5-HAM and WACCM results are shown in Figure 2. Both models show a well developed QBO in the control run (Figure 2, top). WACCM react much more sensitive to the heating of the aerosols after the injection of sulfate. The QBO brakes down at 4 TgS/yr, when ECHAM-HAM shows still an oscillation but with longer phases than in the control run. For an injection of 8 Tg(S)/yr the models are more similar again, but one can still see a stronger impact in WACCM with higher westerly wind velocity. We found that WACCM shows a much stronger heating of the aerosols which results from a vertically much thicker layer of aerosols. The thicker layer causes the aerosols to grow larger. The radius of the particle is important for the radiative forcing of sulfate, as smaller particles scatter better and are more effective than larger particles. The final reason for this different behavior is still open and is going to be investigated in the ongoing cooperation.

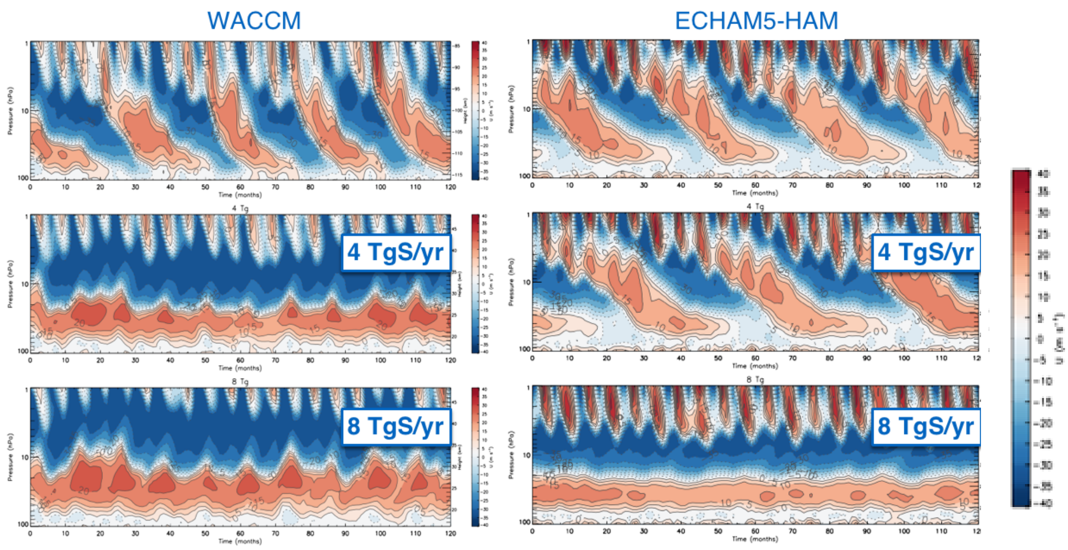

Figure 2: Zonal mean of monthly averaged zonal wind results of WACCM (left) end ECHAM5-HAM (right) at the Equator. Plotted is the control simulation (top), and injections of 4 and 8 Tg(S)/yr.

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