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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 and is currently being continued in the framework of GeoMIP, an endorsed CMIP6 project. The described simulations are a contribution to the GeoMIP testbed experiment accumH2SO4 (Weisenstein and Keith, 2018). The 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.

The overall goal of the project is to significantly increase the level of knowledge about the feasibility and implications of CE options. One of the assumed techniques, the injection of sulfur into the stratosphere, which is also known as stratospheric aerosol modification (SAM), requires detailed knowledge about the microphysical evolution of sulfur and the transport and distribution of the sulfate particles (Niemeier and Tilmes, 2017). Therefore, CE simulations were performed with a middle atmosphere version of the General Circulation Model (GCM) ECHAM5 (T42L90) that is interactively coupled to a modified version of the aerosol microphysical model HAM.

2 Injection of sulfate into the stratosphere – a comparison of the injection of SO_2 or H_2SO_4

Several studies on CE found that the overall radiative forcing (RF) efficiency of a SO_2 injection decreases significantly with increasing injection rate due to increasing sulfate particle size (Niemeier and Timmreck, 2015). The artificial injection of H_2SO_4 could be an alternative as it results in overall smaller sulfate particles and a higher RF efficiency (Vattioni et al, 2019). Therefore, the GeoMIP testbed experiment accumH2SO4 proposes the comparison of a H_2SO_4 injection to a SO_2 injection for different injection strategies and rates. We performed 18 simulations: For both injection species, we tested three injection strategies (equatorial point, 2 points at 30° N and 30° S, 60° wide belt along the equator) and three injection rates (5, 10, 25 Tg (S) yr^{-1}) for injections into three adjacent model layers between 18 and 20 km. The injection of H_2SO_4 was modeled as an injection of accumulation-mode SO_4 (AM-SO_4).

In contrast to an injection of SO_2, an injection of H_2SO_4 results in on average smaller sulfate particles, as the radii do not increase for increasing injection rate (Fig. 1). This results in weaker sedimentation and a higher sulfate burden for a given injection rate (Fig. 2a). More sulfate particles stay with a wet radius in the range of most efficient backscattering (gray bar, Fig. 1), which results in a higher radiative forcing for a given injection rate (Fig. 2b) and leads to a constant RF efficiency independent of injection rate.

Another consequence of less sedimentation and, thus, a higher burden when injecting H_2SO_4 is a stronger stratospheric heating by the sulfate aerosols and a stronger dynamical feedback. The strength of the dynamical feedback increases with increasing injection rate. This is explained by the constant sedimentation velocity due to the constant particle size, but increasingly strong tropical upwelling due to stronger stratospheric heating. Increasing the vertical updraft in the tropics has consequences for the overall efficiency of the sulfur injection. Niemeier et al. (2020) showed that the main reason for the different response of stratospheric dynamics to a sulfur injection in the models WACCM and ECHAM-HAM were differences in the residual vertical velocity.

We can conclude that an injection of H_2SO_4 is more efficient than an injection of SO_2 for all injection strategies and rates. Additionally, due to the constant particle radii with increasing injection rate, the RF efficiency is independent of injection rate for H_2SO_4 injections. These findings are independent of the

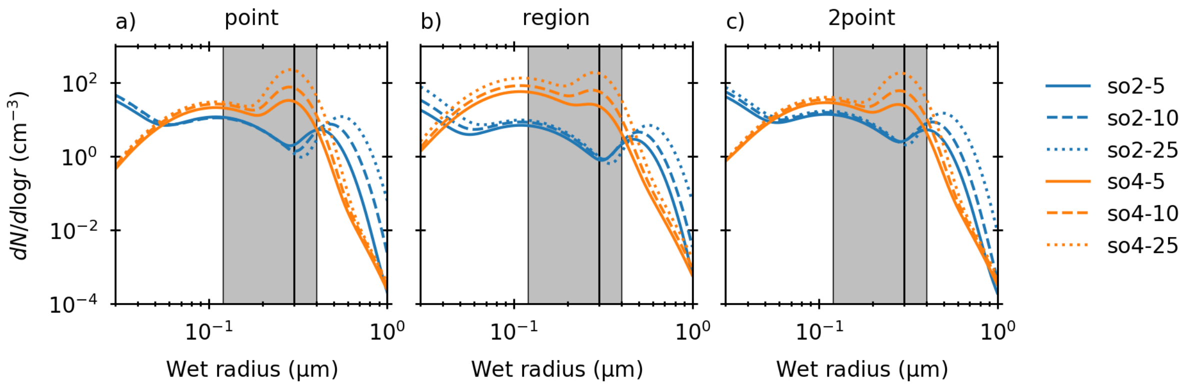

Figure 1: Global mean aerosol size distribution in the injection layer, for the (a) point, (b) region, and (c) 2point injections. The gray bar marks the size range in which the backscattering efficiency of a sulfate particle with a given wet radius is at least 70% of its maximum value, which is achieved for aerosols with a wet radius of 0.3 μm (marked by a thick black line).

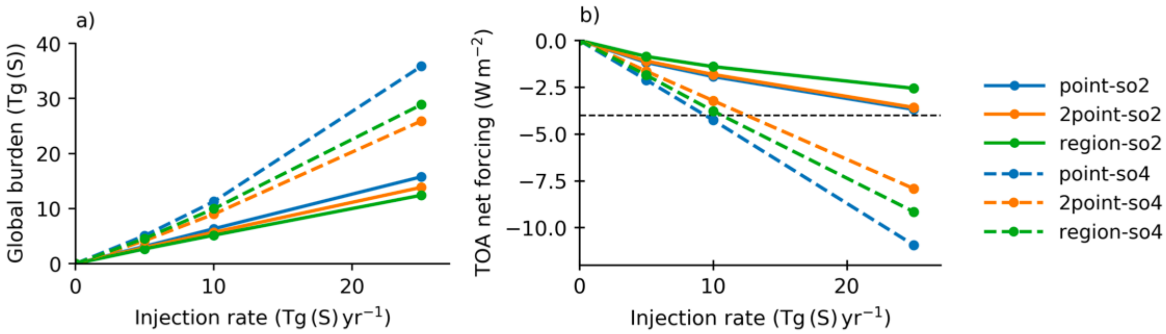

Figure 2: (a) Global artificial sulfate burden and (b) global mean TOA all-sky net RF as a function of injection rate. Within (b), the dashed black line denotes a RF of -4 W m^{-2} for highlighting the different efficiencies of an injection of SO_2 and H_2SO_4.

injection strategy. However, the injection strategy has an important impact on stratospheric dynamics. The heating of the lower stratosphere due to absorption of radiation by the sulfate particles impacts the quasi biennial oscillation in the tropics. This impact can be diminished with injections outside of the tropics as they result in a weaker modification of the temperature gradient within the tropics (see Franke et al. (2020) for more details).

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