Forcing and feedbacks of geoengineering by SO_2 injection into the stratosphere: Analysis of GeoMIP G4 experiment

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Geoengineering is a deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change. Manners of geoengineering for lessening the effects of global warming can be classified into two groups. One is Solar Radiation Management (SRM), which aims to reduce the amount of solar radiation at the surface by increasing the reflection rate. The other is Carbon Dioxide Removal, which aims to reduce the amount of CO_2 in the atmosphere. One of the most probable approaches for SRM is to mimic a large volcanic eruption by injecting sulfate aerosol precursors, such as SO2, into the stratosphere. The sulfate aerosols increase the solar reflectance of the atmosphere, decrease the shortwave radiation (SW) reaching the surface, and cause cooling of surface air temperature. The Geoengineering Model Intercomparison Project (GeoMIP) was established to coordinate simulations with a common framework and to determine the robust effects and responses to geoengineering processes.

In this study, we analyze GeoMIP's G4 experiment, which is designed to inject SO_2 into the lower stratosphere at the equator by 5 Tg/year from 2020 to 2070 with adopting the RCP4.5 scenario as the baseline. This injection rate is about 1/4 of the 1991 eruption of Mount Pinatubo. Some participant models have explicitly calculated the formation of sulfate aerosols from SO_2 and their distribution; whereas some models have just used prescribed aerosol optical depth (AOD) based on the observed AOD after 1991 eruption of Mount Pinatubo. Therefore, a careful comparison is required. In addition, at least cloud amounts, water vapor amounts, and surface albedo can change because of the cooling of the air temperature by SRM. Changes of these amounts affect the reflection and absorption of SW and give some feedbacks to the effect of SRM.

To separately estimate the direct SRM forcing and the feedbacks on each model, we use a single layer atmospheric model for SW transfer. By using this model, we can derive the SW reflection and absorption rates of the atmosphere and surface albedo from the following model outputs: upwelling and downwelling SW at the surface and at the top of the atmosphere. In addition, these calculation can be done with whole-sky amounts and clear-sky amounts, and we can estimate the cloud effects by the their differences. Then, we calculate the contribution of each term described above to the change of net SW at the surface from RCP4.5 to G4, and estimate the direct SRM forcing and the feedbacks. Here, we assume that the change of clear-sky reflection rate is due to the injected sulfate aerosols and that of clear-sky absorption rate is due to the change of water vapor amounts.

Our analysis shows that the globally and temporally averaged SRM forcing ranges widely from -3.6 to -1.6 W/m^2 depending on the models. The SRM forcing on the models with sulfate aerosol calculation is significantly higher than that using the prescribed AOD. This means that the prescribed AOD might underestimate the SRM forcing by 5 Tg/year SO_2 injection. The feedback from cloud amounts and that from water vapor amounts are comparable and range from +0.5 to +1.5 W/m^2 (heating effects). The feedback from water vapor amounts is almost proportional to the cooling of the near-surface air temperature. On the other hand, the cloud feedback shows strong model dependency. The surface albedo feedback works for cooling but it is small (for averaged value).

Our results show the fact that, in the simulation of the geoengineering with SO_2 injection, the uncertainty of the SRM forcing itself is considerably large and that SRM forcing could be decreased by about 50% by the feedbacks from changes in cloud amounts, water vapor amounts, and surface

albedo.

Keywords: Geoengineering, Stratospheric aerosols, Shortwave radiation, GeoMIP

