3.1 Publishable summary

3.1.1 Introduction

In its fourth assessment report (AR4), the Intergovernmental Panel on Climate Change (IPCC) expressed “very high confidence that the global average net effect of human activities since pre-industrial times has been one of warming” (IPCC, 2007a). In the same report, the global average temperature increase up to the last decade of the 21st century with respect to 1980-1999 is projected to be between 1.8 and 4.0 K. Such a substantial climate change is expected to have tremendous implications for humans and the biosphere in general (IPCC, 2007b).

In this context, the study of geoengineering options has been proposed in order to prepare for the case that mitigation efforts fail. “Geoengineering”, or “climate engineering”, is generally understood as the deliberate manipulation of global climate through technical measures. In general, two main classes of geoengineering techniques are distinguished: Carbon Dioxide Removal techniques (CDR) would remove greenhouse gases (GHG) from the atmosphere. Solar Radiation Management techniques (SRM) would attempt to offset effects of increased GHG concentrations by reducing the amount of sunlight absorbed by the Earth.

A global-scale manipulation of the radiative budget of the Earth applying SRM may allow a counterbalancing of the effects of continued GHG emissions on global temperature, but may also result in undesirable side effects. The IMPLICC project (Implications and risks of engineering solar radiation to limit climate change; http://implicc.zmaw.de), funded by the European Union in its Framework Programme 7 (FP7), is designed to study the efficiency, side effects, and economical implications of proposed SRM techniques.

The project concentrates on the following three methods:

a) space borne reflectors (placed at the Lagrangian point between the Earth and the Sun),
b) sulphur injections into the stratosphere,
c) engineering of low level marine clouds through sea salt injections.

Complex climate models (sometimes referred to as Earth system models (ESMs)) are used to quantify the effectiveness and side effects of these geoengineering concepts. Simulations of a climate modified through geoengineering are performed based on IPCC type future emission scenarios. Economic modelling is used to link benefits and side effects of the studied geoengineering concepts.

This intermediate report on activities within IMPLICC includes first results from coordinated numerical simulations with different climate models (3.1.2), results of specific studies concerning the radiative effects from sulphur injections (3.1.3) and from the manipulation of marine clouds (3.1.4), an overview on the work concerning economical implications of geoengineering (3.1.5), and an outlook on future activities and expected results (3.1.6).

3.1.2 The climate response to solar dimming simulated in three Earth system models

Two major guidelines of the IMPLICC proposal were a) to perform the same set of numerical experiments with several state-of-the-art climate models in order to assess the robustness of the results, and b) to base the experiments on climate change scenarios provided in the context of the CMIP5 (Climate Model Intercomparison Project, Taylor et al., 2008) activity for the fifth assessment report (AR5) of the IPCC. This idea was pursued by a broader community beyond just the IMPLICC partners and has led to the development of the internationally coordinated GeoMIP activity (Kravitz et al., 2011) in which IMPLICC partners play a distinct role. The original IMPLICC plan for numerical simulations was adjusted to the GeoMIP strategy.

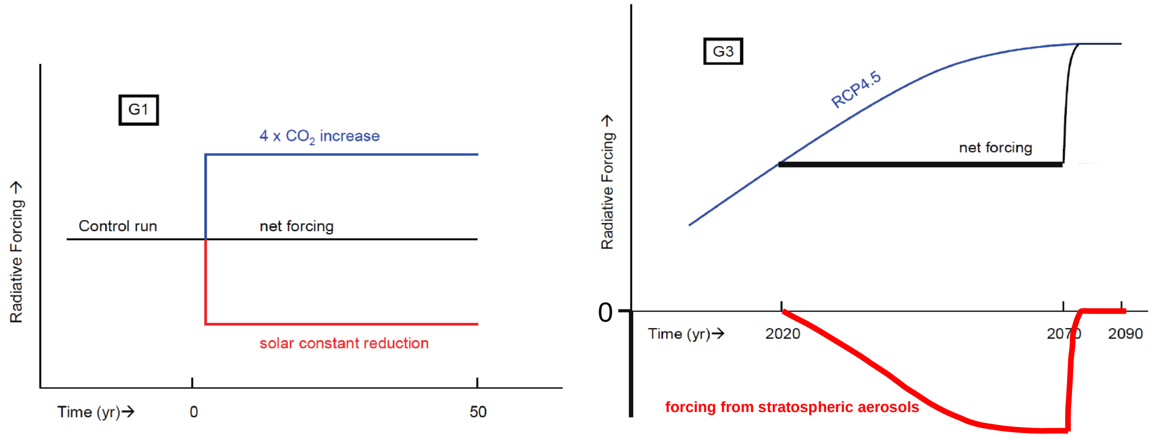

Figure 1: Simulation strategies in the GeoMIP/IMPLICC numerical experiments G1 and G3. Figures are adapted from Kravitz et al. (2011).

Fig. 1 shows strategies for two of the experiments to be performed within IMPLICC/GeoMIP. Experiment G1 (Fig. 1, left) follows an idealized scenario where the forcing from an immediate quadrupling of the carbon dioxide concentration is balanced by a reduction of the solar constant (analogous to the effect of space reflectors). The rationale for such an experiment is to compare the difference of model response to a very simple but strong forcing where the signal-to-noise ratio is large. Experiment G1 has been performed by the ESMs operated by the IMPLICC partners CEA (IPSL-ESM), MPI-M (MPI-ESM) and UiO (NorESM). Some of the preliminary results are robustly simulated by all models: To balance the global temperature, i.e. to keep it at the level of the preindustrial control simulation (PiCS), the necessary reduction of the solar forcing is larger (on the order of 10 to 20%) than the forcing estimated from the change in CO_2. This means that the efficiency of shortwave solar forcing is smaller than that of longwave CO_2 forcing. The climate in such a geoengineered world would, however, not be the same as in preindustrial times. Fig. 2 shows the latitudinal dependence of the temperature response to the forcing in G1 (with respect to PiCS). A common result among the models is that high latitudes (and in particular the Arctic) still tend to be warmer under geoengineering while low latitudes would cool slightly. The solar dimming is obviously more effective in regions with strong insolation.
Global precipitation is reduced in experiment G1 (on the order of about 3-4% with respect to PiCS) although one should note that a quadrupling of CO_2 alone would strongly enhance precipitation. This effect was already discussed by Bala et al. (2008) and is now confirmed in our IMPLICC simulations with more complex models.

3.1.3 Geoengineering by sulphate injection into the stratosphere

Fig. 1 (right panel) shows the design of IMPLICC/GeoMIP experiment G3, in which it is intended to limit climate forcing to remain constant at the level reached in 2020. This approach should allow limiting the increase of globally averaged temperatures at a value of less than 2K with respect to preindustrial values. The intention is to balance the increase of GHGs after 2020 by sulphur injections into the stratosphere which would lead to the build-up of an aerosol layer causing reflection of sunlight. However, it is disputed what quantity of sulphur emissions at which location would be necessary to balance a given GHG forcing, and how strong the effect on the ozone layer and global atmospheric circulation would be.

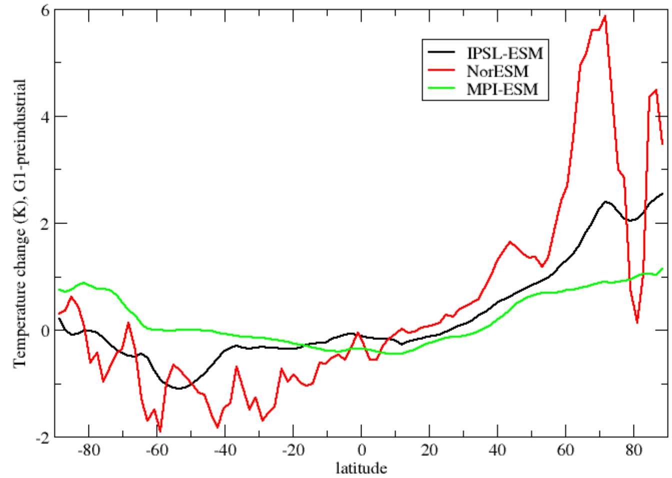

Figure 2: Zonal mean surface temperature anomaly in experiment G1 (4xCO2 balanced by reduced solar constant) relative to a preindustrial control simulation. Results of IPSL-ESM (black) and MPI-ESM (green) are averaged over 50 years, NORESM results (red) over 10 years. Note: In the graphs for IPSL-ESM and NorESM a temperature bias has been removed that was resulting from an inexact balancing of the radiative forcing.

To reduce the uncertainty concerning these questions, initial stratospheric sulphur injection scenario experiments were carried out at MPI-M with the Middle Atmosphere ECHAM5 global circulation model coupled to the Hamburg Aerosol Model (HAM). A major outcome of this study (Niemeier et al., 2010) is that higher injection rates (which would be in practice more difficult to realize) would lead to larger forcing simply by the increase optical depths, although the additional effect becomes smaller as the injection rates become larger, since larger particles form and sediment faster, reducing the aerosol lifetime. Fig. 3 compares aerosol forcings resulting from different emission rates and strategies in our work to results from earlier studies. The simulated aerosol effect in our work is smaller than assumed in a simpler model setup (e.g. Robock et al., 2009), and larger than in a more comparable study by Heckendorn et al. (2009) which reflects the existing uncertainty concerning aerosol microphysics in the stratosphere and hence the resulting optical properties and

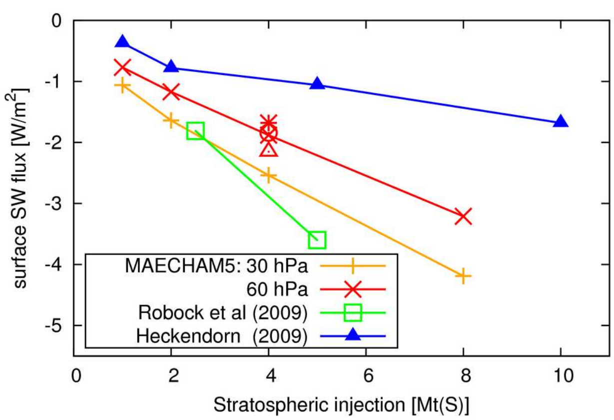

Figure 3: Radiative forcing from continuous stratospheric sulphur injections from different studies. Yellow and red: our own work (Niemeier et al., 2010), blue: Heckendorn et al. (2009), green: Robock et al. (2009). Yellow and red indicate emission levels of 30 and 60 hPa, respectively. Blue and green should be compared to the 60 hPa emission scenario.

removal of sulphate aerosols.

While all these studies concentrated on emissions in the tropics, we have also performed sensitivity studies assessing the effectiveness of emissions at different latitudes using passive tracers in the

MPI-C version of the ECHAM5/MESSy global circulation model with Atmospheric Chemistry (EMAC). According to these experiments, polar injections may provide a realistic alternative, even though the aerosol is removed faster from the atmosphere, since it could nevertheless be injected at much lower altitudes because of the lower tropopause. Further work has also been done concerning an improvement of the sedimentation algorithms used in the aerosol models to reduce numerical artefacts in the simulations.

3.1.4 Geoengineering by manipulation of marine clouds

In order to compare different geoengineering techniques we plan to perform a G3 type experiment but rather than using sulphur injections we would implement cloud whitening to balance the GHG forcing. The idea behind this geoengineering technique is that injections of sea salt in the marine cloud layer are expected to raise the cloud droplet number concentration and reduce the cloud droplet size, thereby increasing cloud albedo (e.g. Latham et al., 2008). It is debated what amount of radiative forcing could be achieved in practice by this technique. It is however clear that a cloud's susceptibility and whitening response to a given change in cloud droplet number concentration would depend on the region. To quantify this we modified the concept of "absolute susceptibility" (Platnick and Oreopoulos, 2008) by introducing a "total susceptibility" that is normalized and also reflects the solar zenith angle, as well as cloud cover. Calculating this parameter from observational data it was identified that in general the most sensitive areas are found between 30°S and 30°N over the Pacific and Indian Oceans.

Furthermore, a set of sensitivity simulations has been carried out using NorESM which has a sophisticated treatment of aerosol-cloud interactions (Hoose et al., 2009). In two experiments the same sea salt flux was added uniformly over the oceans. In the former experiment (SS1), the added sea salt injection particles had a (dry) radius of 0.13 µm (as in Latham et al., 2008) while in the latter experiment (SS2) a particle radius of 0.022 µm was assumed. The results of the two experiments were strikingly different. In SS1 the globally averaged negative radiative forcing (resulting from brightening by reduced cloud droplet radii) was only 50% larger in magnitude than found in a study by Latham et al. (2008), even though our injected sea salt mass is 70 times higher. This is likely due to more realistic assumptions concerning cloud microphysics in NorESM. In SS2, the sea salt injection led, surprisingly, to an increase in cloud droplet radius because of interactions with atmospheric sulphate. The results of these experiments indicate that the effects from the suggested emission of sea salt would depend crucially on the design of the implementation. Furthermore, effects may be quite different to those expected from first order assumptions, because of the complicated and not completely understood microphysics of aerosol-cloud interaction.

3.1.5 Economic implications of geoengineering climate

The work on the economic implications of geoengineering is aimed at comparing costs for geoengineering methods to those of climate change and conventional mitigation (i.e. emission control). However, the choice within IMPLICC and GeoMIP to use the IPCC RCP4.5 scenario as a reference from which a further reduction of radiative forcing should be reached via geoengineering makes the comparison with corresponding emission reductions difficult. This is because RCP4.5 already implies substantial emission cuts during the 21st century, and it is difficult to build an economic model for a further reduction of radiative forcing which would be equivalent to geoengineering. First studies with the GRACE_imp model (Aaheim and Wei, 2010) have therefore concentrated on the implications resulting from emission control necessary to reduce the forcing from the RCP8.5 scenario to RCP4.5. Major results are that the wealthiest regions seem to be the least affected because the growth rate is anyhow expected to be relatively low. In faster growing regions this reduction would imply a strong shift from industrial sectors towards service sectors. This may be a result of enforcement of higher quality and longer lasting industrial products, as the climatic impacts are being internalized in the cost of production.

3.1.6 Conclusions and Outlook

Our numerical sensitivity studies of geoengineering techniques of sulphate and sea salt injections carried out so far have revealed that there is still a large uncertainty concerning the magnitude of the radiative effects caused by these methods. For instance, the forcing resulting from the manipulation of marine clouds may be significantly smaller than assumed in earlier studies, and it may furthermore depend strongly on the specific technique that would be implemented. The accurate estimation of such effects in numerical models depends on not well constrained and sophisticated parameterizations of aerosol and cloud microphysics. This suggests, aside from our model results, that field experiments (or in the case of stratospheric sulphur, comprehensive observations of aerosol clouds from future volcanic eruptions) may be necessary to more accurately assess the potential of these methods. Numerical simulations with comprehensive global climate model should however be able to assess climate effects of an assumed forcing. Results from the G1 experiments indicate that there are some robust features surfacing across the IMPLICC models such as the global reduction of precipitation resulting from geoengineering. Strongly adverse effects on the hydrological cycle, and in particular on the monsoon seasons and thereby on life of a huge number of humans in Asia and Africa, have been suggested earlier (Robock et al., 2008). It is very encouraging that as a result of collaboration between our project and other existing activities the model comparison (at least for a subset of experiments defined in GeoMIP) will be done not “only” for the three IMPLICC models, but for a larger number of models worldwide. These simulations will find their way into the upcoming IPCC AR5 and provide substantial information to the public and policy makers to guide further research and policy development on geoengineering.

3.1.7 References

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