IMPLICC: Implications and risks of engineering solar radiation to limit climate change

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Synthesis report for policy makers and the interested public

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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". 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°C. Such a substantial climate change is expected to have tremendous implications for humans and the biosphere.

In this context, various geoengineering options have been proposed in order to prepare for the case that mitigation efforts are insufficient to stop the most drastic impacts of climate change. “Geoengineering”, or “climate engineering” (CE), is generally understood as the deliberate manipulation of global climate through technical measures. Two main classes of geoengineering techniques are considered: Carbon Dioxide Removal (CDR) techniques would remove CO_2, the most important anthropogenic greenhouse gas (GHG), from the atmosphere, while Solar Radiation Management (SRM) techniques 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 and risks. 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), was designed to study the effectiveness, side effects, risks, and economic implications of proposed SRM techniques.

This document is intended to present major results of the project to the interested public.

2. The scientific approach

One central question that guided the work within IMPLICC was the following: What would a climate engineered through SRM look like, in terms of multiple aspects of characterizing climate (not just global mean surface temperature)? As for any other question related to the future climate, numerical climate models are useful tools to tackle this question. Given the uncertainties in many details of the formulation of climate models, the community of climate researchers has organized model intercomparison projects (MIPs) in particular to project the future climate under specified greenhouse gas emission scenarios. Comparing results from several models, each performing exactly the same well-defined numerical experiments, allows one to identify which characteristics of a projected future climate appear to be robust, and hence are likely to be based on well-understood physical mechanisms. Climate projections that differ strongly among the participating models depend on the differences in the formulation of the models and need to be considered as highly uncertain.

IMPLICC implemented such a model intercomparison project to better understand the climate response to potential future SRM. The idea was to define SRM scenarios and simulate them with three state-of-the-art Earth system models (ESMs) operated by the IMPLICC partners: IPSL/CEA (model: IPSL-CM5A), MPI-M (model: MPI-ESM), and UiO (model: NorESM). However, given that wider interest in such a numerical modelling exercise evolved once IMPLICC was established, IMPLICC joined forces with the larger international community, and an IMPLICC workshop in 2009 was used to define numerical experiments under the umbrella of GeoMIP, the geoengineering model intercomparison project (Kravitz et al., 2011).

The IMPLICC project concentrated on the following three SRM methods:

a) space borne reflectors (e.g., placed at the Lagrangian point between the Earth and the Sun),

b) sulfur dioxide or sulfuric acid injections into the stratosphere,

c) engineering of low level marine clouds through sea salt injections.

The impact of method a), realized in the models by reducing the solar constant, has been studied via balancing the radiative forcing of an abrupt fourfold increase of the pre-historical CO_2 concentration (GeoMIP scenario G1). Climate effects of methods b) have been studied in multi-model simulations following the GeoMIP scenario G3 (Kravitz et al., 2011). This scenario builds on the CMIP5 (Taylor et al., 2012) moderate greenhouse gas emission scenario RCP4.5 simulated by many climate modelling centers for the next IPCC assessment report. Under G3 it is assumed that SRM would be employed to keep the future level of climate forcing from GHGs at the level reached in the year 2020, i.e., to balance the future climate forcing from additional GHGs by climate engineering. This is realized through increasing sulfur emission rates in the stratosphere until the year 2070. In order to study the potential rapid climate change when SRM is discontinued, the G3 scenario is continued beyond 2070, but with the SRM measures switched off. Method c) is studied under a scenario identical to G3 but using the manipulation of clouds instead of sulfate aerosols. This scenario, called G5, is not yet included in the GeoMIP project, rather only within IMPLICC.

Besides the pure climate model studies, effectiveness and implications of methods b) and c) have also been studied using specific numerical models including atmospheric chemistry (the EMAC model operated at MPI-C) and aerosols (NorESM). Furthermore, economic modelling is used to study potential economic effects of SRM in different regions of the world based on the climate model results.

3. CE through the reduction of solar irradiance – What would an engineered climate look like?

Changes in greenhouse gas concentrations and solar radiation have different impacts on the global radiation budget. Greenhouse gases influence the long-wave terrestrial radiation relatively homogeneously on the global scale. Dimming the sun, for example by installing reflectors in outer space, affects the short-wave part of the radiation budget. The strongest effect can be found where solar radiation is most intense – thus, all year round in the tropics and during summer at the higher latitudes.

All three IMPLICC models mentioned above, plus the HadGEM2 model of the United Kingdom Met Office (UKMO), have run the same three scenarios: 1) starting from preindustrial conditions and allowing the simulation to continue on with the pre-industrial conditions; 2) applying a fourfold increase in the CO_2 concentration (“global warming”); and 3) in addition to the CO_2 increase, applying a reduced solar constant at the same time (“dimming the sun”) to balance the total global radiative forcing. This G1-scenario of GeoMIP is not realistic since such a sudden CO_2 increase has not happened and is not expected to happen. However, a radiative forcing that corresponds to four times the pre-industrial CO_2 concentration by the end of the 21st century cannot be ruled out, according to the business-as-usual scenario RCP8.5. By using such an extreme scenario it is made certain that the simulated climate signals clearly stand out from natural climate variability.

In many respects, the models involved react robustly to this very drastic radiative forcing. In the model experiments, the effect of the increase in the greenhouse gas concentration on the global radiation budget is balanced by the reduction of solar irradiance – accordingly, the global mean temperature remains at a pre-industrial reference level. Interestingly, 25% more SRM than expected is required since a reduced global cloud cover appears in the scenario, warming the planet. Also, the temperature does not stay at the reference level all over the world but is generally slightly higher than in the reference simulation at the higher latitudes and over continents (up to 1°C) and lower in the tropics and over the oceans. Compared to a quadrupling of CO_2, however, the temperature changes are modest, because unmitigated quadrupling of CO_2 leads to a global mean surface temperature increase of 5 to 6°C in the models.

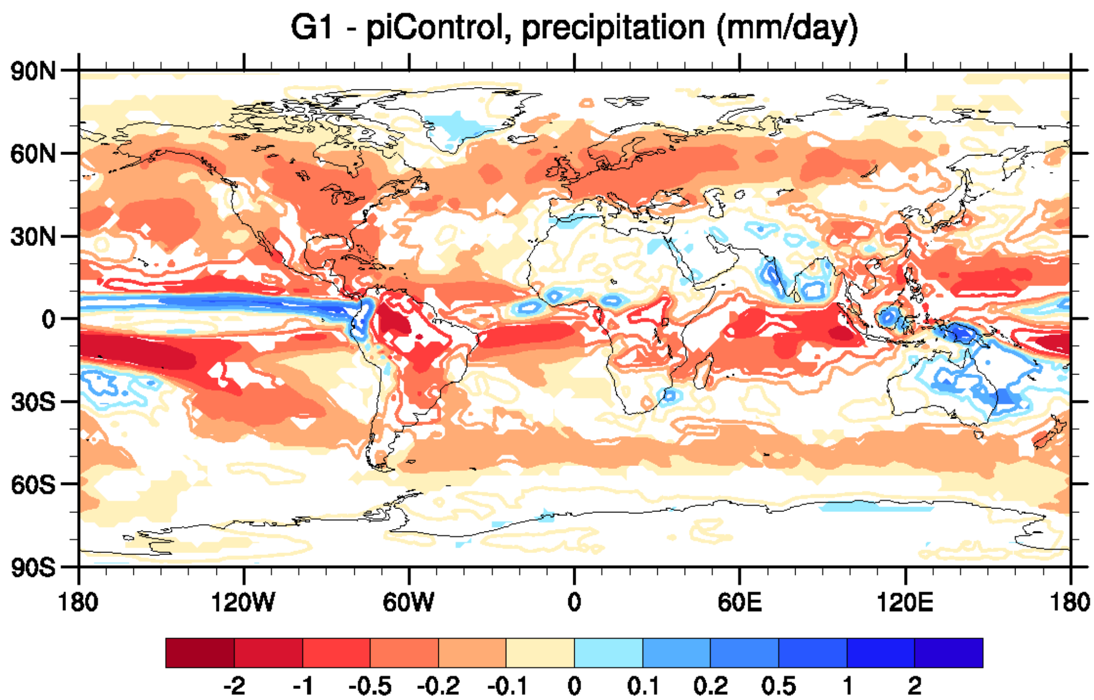

Figure 1*: Differences in precipitation (mm/day) between the simulations G1 (with climate engineering) and the preindustrial control run, averaged over the four ESMs. In regions with filled colour shading all models agree in the sign of the response.*

The G1 scenario effects on precipitation are significantly stronger: the SRM applied together with the quadrupled CO2 results in a decrease in the global mean precipitation by about 5%. In the simulation in which quadrupled CO_2 is not compensated by SRM, precipitation, on the contrary, would increase by about 9%. On the regional scale, changes in precipitation can be even stronger in the SRM scenario than only due to increased greenhouse gas concentrations. While in the latter case a clear reduction in precipitation, e. g. in the Mediterranean is simulated, this pattern shifts northwards when the solar dimming is applied. Over the vast land masses of northern Eurasia as well as over North and South America, a large-scale decrease in precipitation by more than 10% is simulated for this G1 scenario (see Fig. 1).

The model intercomparison hence shows that climate engineering by using solar radiation management methods (here: reducing the solar constant, which can be compared to installing reflectors in outer space) can reduce some aspects of climate change globally, but will not restore a historical climate state such as the one of pre-industrial times. It will instead create an entirely new climate. Even if global mean temperatures could be lowered to the pre-industrial level, regional patterns of temperature still change, and the global amount and regional patterns of precipitation would change significantly. Further details of this intercomparison study are given by Schmidt et al. (2012).

4. Implications of CE through injections of sulfur into the stratosphere

Arguably the most discussed SRM method is the injection of large amounts of sulfur dioxide or sulfuric acid into the Earth's stratosphere (situated at ~15-50 km altitude). The sulfur dioxide or sulfuric acid is then transformed into sulfate aerosol particles, which would build up, subsequently reflecting additional solar radiation, thus changing the atmospheric energy budget and decreasing the temperature at the Earth's surface. This is analogous to the climate effect associated with the injection of sulfur dioxide into the stratosphere through volcanic eruptions. For example, the eruption of Mt. Pinatubo in 1991 caused a reduction of global average surface temperature that reached a maximum of about 0.5°C.

Questions with respect to this method concern: the resulting climate; the quantification of the expected side effects on stratospheric ozone; and the effectiveness of the method, i.e. the amount of sulfur needed to reach a certain climate effect.

With respect to the amount of sulfur needed, Niemeier et al. (2011) showed in a numerical study within IMPLICC that simple extrapolation from volcanic eruption data may not be accurate enough to estimate the amount of sulfur necessary to obtain a specific cooling. The complex aerosol microphysics may lead to a faster than expected removal from the atmosphere and hence an underestimation of the necessary amount of sulfur. However, a comparison with another study (Heckendorn et al., 2009) shows that even complex aerosol calculations are still highly uncertain. With another model operated at MPI-C, Benduhn and Lawrence (2012) have studied specific aspects of sulfur injections. They showed that the injection of sulfur either as sulfuric acid or as sulfur dioxide would differ strongly with respect to the formation and growth of the sulfate particles. For the release of sulfuric acid into the stratosphere to be simulated faithfully in a global model, the subscale character of particle formation needs to be taken into account, and the corresponding injection parameters should be chosen carefully. The particles that rapidly form in the expanding plume after injection have to be small enough to limit sedimentation losses, yet large enough to limit upward transport, which results in more rapid dispersion and eventual loss through the Brewer-Dobson circulation, as well as an enhanced potential to cause ozone depletion. In contrast to releasing sulfuric acid, the release of sulfur dioxide would be much more difficult to steer, due to the longer chain of processes linking the oxidation of sulfur dioxide to the eventual formation of sulfate particles.

Numerical simulations of the effect of sulfur injections on stratospheric ozone within IMPLICC (with the EMAC model operated at MPI-C) have confirmed earlier studies. In particular, in the context of the polar winter and the linked formation of a polar vortex, ozone over both poles, especially the Antarctic, tends to be further depleted through the additional aerosols and the related formation of reactive chlorine species. On the other hand, the ozone column outside the polar areas tends to be reinforced as a consequence of the aerosol serving as an additional sink of ozone degrading nitrate. These effects are, however, relatively small, being on the order of about 5-10% for an injection of 2 Mt(S)/y (an amount that could approximately balance the increase in GHG forcing between the years 2020 and 2035 in the moderate emission scenario RCP4.5). Nevertheless the impact on ozone is perhaps still large enough to be of concern, especially over populated regions near the poles.

Potential climate effects of sulfur injections have been studied by comparing results from the three IMPLICC ESMs for the G3 scenario described in Section 2. As expected from the design of the numerical experiments, the temperature increase from 2020 to 2070 is small in comparison to the increase of about 0.7 to 1.2°C simulated under the emission scenario RCP4.5 without SRM. Global mean precipitation under G3 is on average in the three models slightly reduced in 2070 compared to 2020. The regional patterns of precipitation response in the three ESMs do not agree well; however, changes are in general small. This is not unexpected, as under this scenario only a moderate additional climate forcing, projected under RCP4.5 between 2020 and 2070, is balanced by SRM. Balancing a larger forcing would likely lead to much stronger climate responses as discussed in Section 3. The IMPLICC simulations confirm, however, the risk of very rapid climate change if SRM is terminated abruptly. Stopping SRM measures in 2070, as done under this scenario, would cause the global mean temperature to increase to being close to the scenario without SRM in less than ten years.

The climate effects of sulfur injections in comparison to those of other SRM methods will be discussed in Section 6.

5. Implications of CE through the manipulation of marine clouds

It has been known for about 20 years that the strong cooling effect of marine stratiform clouds depends on the size of the cloud droplets. If a given amount of water is distributed on many small droplets the reflection of solar irradiance is stronger than if the same amount is distributed on few large droplets. It has been suggested that the injection of additional sea salt aerosols into regions with low-level clouds would enhance the number of cloud condensation nuclei. Water vapor can condense onto these and lead to the formation of more and smaller cloud droplets and, hence, brighter clouds that cool the climate. Contrary to the methods of SRM discussed above, radiative effects of this method would be much more regional and hence the potential climate effects can be expected to be different. Besides this, open questions remain concerning the effectiveness of the method.

Within IMPLICC, Alterskjær et al. (2012) used satellite observations and the NorESM to investigate which regions over the ocean are the most sensitive to deliberate increases in cloud droplet number concentration. They found high sensitivities in the tropical region between about 30°N and 30°S, in particular off the west coasts of the continents. This agrees with earlier studies. But they also found that the effectiveness of cloud seeding maybe smaller than expected from simple estimates because it can be inhibited by different processes. This includes the condensation of gaseous sulfuric acid on the injected particles, which reduces the formation of cloud condensation nuclei by sulfuric acid itself.

Other important new results of numerical studies performed at UiO show that injected sea salt may also have a strong direct radiative effect in regions where it does not immediately serve as condensation nuclei. This effect is, however, quantitatively different among numerical models and needs to be studied further. An additional important result is that the effect of sea salt emissions on clouds crucially depends on the size of the emitted particles (Alterskjær and Kristjánsson, 2012). If particles of a larger or smaller than optimal size are emitted, the effectiveness of this SRM method could be strongly reduced or even inverted, i.e. leading to an increase in surface temperatures as opposed to the desired cooling. Likewise, if the injected sea salt mass is very large, the effectiveness is reduced because of a suppressed supersaturation due to excessive competition for the available vapor.

Global mean temperature effects of this marine cloud brightening are similar to those of sulfur injections. With the right amount of emissions in the models, the temperature increase after 2020 can be slowed down considerably, but after a potential termination in 2070 the climate change is very rapid, i.e. the engineering is almost forgotten within about 10 years. As the “amount” of SRM in this numerical experiment is small compared to the idealized G1 experiment of section 3, the effect on precipitation is relatively small. The two models having performed the marine cloud experiment so far (NorESM and MPI-ESM) show, however, similar patterns of precipitation response to the idealized experiment, with reductions in middle to high latitudes, in particular over the North-American continent.

6. Comparing climate effects of different SRM methods

In order to understand differences in the climates produced by different CE methods, we have simulated a scenario of the G3-type, i.e. ramped-up climate engineering from 2020 to 2070, for different methods. Besides the sulfur injection and cloud brightening approaches discussed in sections 4 and 5, the MPI-ESM was used to perform two further numerical experiments: one for a simple reduction of solar irradiance, as might be realized by space mirrors, and one with greenhouse gas concentrations fixed at 2020 levels, which can be interpreted as a massive mitigation or carbon dioxide removal scenario. Fig. 2 (left panel) shows a similar small temperature increase for all four approaches which is due to the inertia of the climate system. In the case of cloud brightening, the temperature in 2070 is almost 0.2^{o}C lower than for the other methods, indicating probably an overestimation of the amount of sea salt emissions needed to reach a certain cooling. The right-hand panel of Fig. 1 shows that global mean precipitation responds differently in the four scenarios. A fixing of GHG concentrations leads to a further increase of precipitation due to the increasing global mean temperatures. The three solar radiation management scenarios show, however, almost no change for the space-mirror case, and decreasing precipitation for the two other techniques. This is at least partly related to both sea salt and stratospheric sulfate aerosols not only reflecting solar irradiance but also having a greenhouse effect. Cloud effects and the lower temperatures in the case of cloud brightening may also contribute to the different evolutions of global mean precipitation. However, these results suggest that the strong precipitation effects caused by a pure reduction of solar irradiance in the massive SRM scenario G1 (Section 3) might be even stronger if one of the other two SRM techniques was employed.

Regional climate responses can also be expected to differ between the different techniques, but to properly estimate such effects future multi-model analyses will be needed.

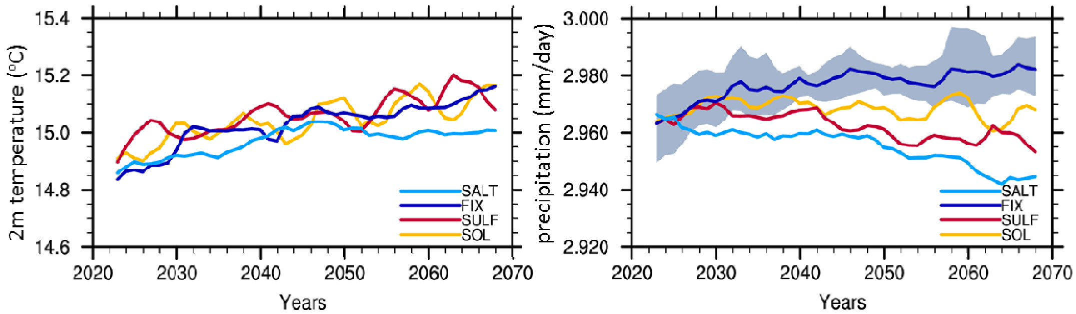

***Fig. 2**: Time evolution of global mean temperature (°C, left) and precipitation (mm/day, right) simulated with the MPI-ESM under four different scenarios of type G3, i.e. where it is attempted to keep the climate forcing constant at 2020 levels through different methods. SALT: manipulation of marine clouds; FIX: GHG concentrations fixed at 2020 levels; SULF: injection of sulfur into the stratosphere, SOL: reduction of solar irradiance. All results are 5-year running means averaged over ensemble simulations with three members. The shading around the precipitation time series from FIX indicates maxima and minima of the ensemble members.*

7. Economic Implications of CE

The numerical economic general equilibrium model GRACE (operated by CICERO) was used to estimate economic implications of the IMPLICC climate engineering scenarios. The model calculates economic activity and trade between eleven world regions influenced, among other factors, by climate change signals in temperature and precipitation. The studied scenarios are the high-emission scenario RCP8.5, the moderate emission scenario RCP4.5 which is realized in GRACE by invoking charges on CO_2-emissions, and the G3-type SRM scenarios using sulfur and sea salt emissions (as discussed in Sections 4 and 5) to further limit the climate change experienced under RCP4.5. Climate change information on temperature and precipitation as calculated by the IMPLICC-ESMs was used in the economic model.

It should be noted that the limitations of analyzing the costs and benefits of climate engineering by general equilibrium models based on climate projections are many. In particular, most of the numerical estimates are highly uncertain. This includes the climate projections, the economic data and the linkages between climate indicators and economic activities, which we must partly consider unknown. Another important criticism is that possible side-effects of solar radiation management other than on monthly mean temperature and precipitation have been ignored in this study, as for example potential changes in the magnitude and frequency of extreme events. The main reason is that side-effects and their social and economic consequences are poorly understood, and there are few, if any, studies to base estimates on. On the other hand, this study addresses a few issues that previous studies have left out. While impacts are usually explained solely by the change in mean temperature, they are related also to changes in precipitation here. Impacts are moreover weighted depending on where the activities take place: over arable and forested land in agriculture and forestry, respectively. Other impacts are weighted according to population density. As a consequence, changes in coastal areas tend to have a greater impact than changes elsewhere.

On this background, we draw the following conclusions:

1) In combination with strong efforts to reduce emissions of greenhouse gases (as assumed in the RCP4.5 scenario), the economic benefits of further reducing radiative forcing by solar radiation management are likely to be negative. This is partly because SRM changes precipitation patterns with negative economic impacts, and partly because there are benefits of a small warming effect in some regions. Possible negative side-effects of geoengineering will add to the costs of these technologies.

2) The responses differ among regions. While GRACE calculates that SRM under the G3 scenario causes a GDP reduction in East Asia by 1.2 percent in 2070 in comparison to RCP4.5, Latin America and Africa benefit up to 0.4 percent in the same year.

3) Even though the expected impacts of SRM are negative when compared to the RCP4.5 scenario, geoengineering may turn into an option with positive benefits if the impacts of global warming at moderate levels suffice to reach tipping points for natural processes and ecosystems, which are not considered in this study.

4) If solar radiation management is imposed in a future with higher emissions, the potential for benefits may become large. In the RCP8.5 scenario, which causes a warming of 5 to 6°C in populated areas in 2100, negative impacts of climate change lead to reductions between 1.5 and 9 percent in GDP, depending on region. However, at such a level of warming, the impacts of both climatic changes and of a resulting attempt to mitigate warming by solar radiation management must be considered unknown.

8. Summary and conclusions

Within the IMPLICC project, five partner institutes from France, Germany and Norway have studied the effectiveness, side effects, risks and economic implications of climate engineering through different solar radiation management techniques suggested to limit climate change. The main tools used in these studies were state-of-the-art numerical Earth system models (in some cases augmented by specific treatments of atmospheric aerosols and chemistry) and an economic model. One central question was what climate would result from the application of three different CE techniques: the reduction of solar irradiance (through space mirrors); the enhancement of the reflection of solar radiation through stratospheric sulfate aerosols; and the manipulation of marine clouds through injection of sea salt. One novel aspect of IMPLICC in the context of climate engineering research was the implementation of a model intercomparison study in order to identify robust climate response patterns.

In an idealized experiment with large greenhouse gas forcing balanced globally by the reduction of solar irradiance it was shown that it may be possible to compensate the increase of global mean temperature. However, the increase in global total precipitation that is expected in scenarios with enhanced greenhouse gas concentrations would be overcompensated by solar radiation management: a geoengineered climate would have less precipitation than a natural climate of the same global mean temperature. The model intercomparison showed that precipitation decreases – under the chosen scenarios - would particularly affect large land masses in the mid-latitudes of the Northern hemisphere, i.e. Canada and the US, central and northern Europe and Asia.

The simulation of a scenario with a much smaller degree of geoengineering, where just the increase of climate forcing through a moderate greenhouse gas emission scenario after the year 2020 would be compensated, showed, not surprisingly, a much smaller climate impact. Because of the weakness of the forcing, the regional patterns of the simulated responses are also less robust than under strong forcing. It was, however, clearly shown that an abrupt termination of climate engineering efforts would lead to very rapid climate change.

The estimation of economic implications of climate change and climate engineering on long time-scales has obvious limitations. However, our simulations suggest that additional climate engineering under a moderate mitigation scenario may not be economically advantageous. This could be different under high-emission scenarios, but also it is then unclear if the economic importance of side-effects would become significant.

IMPLICC has also made progress on microphysical processes involved in the aerosol-based radiation management methods, which help determine their effectiveness. It has become clear that the effectiveness of the methods depends strongly on the implementation, e.g. on the size of emitted sea salt particles. However, uncertainties concerning the amount of aerosol necessary to reach a certain climate effect remain.

It has become clear during the course of the project that some of the remaining uncertainties concerning implications of climate engineering are caused by limited understanding of climate processes in general, which are not necessarily specific to climate engineering. The manipulation of marine clouds, for example, is based on aerosol-cloud interaction processes which are one of the big open questions of climate research, independent of the origin of aerosols. Injecting sulfur into the stratosphere would not only have radiative but also dynamical effects. Dynamical stratosphere-troposphere coupling would need to be better understood in order to fully appreciate the effects of such climate engineering.

Finally, it needs to be noted that the climate response is only one aspect that has to be considered when the implementation of climate engineering techniques is discussed. Other potential side effects specific to some methods, as well as political, ethical, legal and further economic implications have to be taken into account. But the potentially strong climate responses discussed here suggest that climate engineering cannot be seen as a substitute for a policy pathway of mitigating climate change through the reduction of greenhouse gas emissions.

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