The FP7 project IMPLICC

Implications and risks of engineering solar radiation to limit climate change

Final publishable summary report

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1. Executive summary

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. Numerical results of these simulations are made available to the international scientific community for further exploitation that is currently ongoing for example within the international “Geoengineering Model Intercomparison Project” (GeoMIP).

The estimation of economic implications of climate change and climate engineering on long time-scales has obvious limitations. However, our simulations suggest that climate engineering under a moderate emission 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 major 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 also need to be taken into account.

2. Description of project context and objectives

The central goal of the IMPLICC project was to better understand effectiveness, side effects and economic implications of climate engineering (or "geoengineering") methods suggested to limit climate change. The next two sections describe the scientific context and project objectives as given at the beginning of the project in 2009. However, since then the discussion of and scientific research on climate engineering has increased considerably. Therefore, Section 2.3 very briefly describes changes of the context and with it also a modification of some of the goals that occurred during the duration of the project.

2.1 Scientific and societal context

There is increasing scientific evidence indicating that anthropogenic emissions of greenhouse gases (GHG) have a significant impact on Earth's climate. In its fourth assessment report (AR4), the Intergovernmental Panel for Climate Change (IPCC) has 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, best estimates were given for the projected global average future temperature increases up to the last decade of the 21^{st} century with respect to 1980-1999. Depending on the assumed emission scenario these best estimates lie in the range of 1.8 to 4.0 K (IPCC, 2007a). Such a substantial climate change is expected to have tremendous implications for humans and the biosphere in general (IPCC, 2007b).

<u>Strategies to limit projected climate change in case of GHG reduction failure</u>

With the Kyoto protocol, agreed on in 1997, the United Nations took a first step to limit the increase of the atmospheric content of GHGs by limiting anthropogenic emissions. Exploratory engineering studies are also underway to prevent carbon dioxide (CO_2) from entering the atmosphere by applying carbon capture and sequestration in long-term underground or sub-seafloor storage facilities. Despite these attempts, carbon dioxide concentrations in the atmosphere have continued to rise, due to accelerating anthropogenic emissions, and the radiative forcing of carbon dioxide increased by 20% from 1995 to 2005 (IPCC, 2007a). Consequently, there is a growing urgency to design new measures for limiting climate change to an acceptable level. As an alternative to emissions reductions – whether by reduced energy consumption, by improved efficiency, or by carbon capture and sequestration at the sources - and to prepare for possible failure of emission reduction attempts through international agreements, the public and scientific communities have for many years discussed the possibility of "climate engineering", or *the deliberate manipulation of the Earth system to manage the climatic consequences of human population and economic expansion* (Schneider, 2001). A couple of years ago, this discussion has been intensified, especially in the scientific community, due to an article by Paul Crutzen, in which he suggested considering and investigating methods of geoengineering Earth's climate in order to provide sound scientific support to policy makers for climate change mitigation decisions (Crutzen, 2006).

Crutzen (2006) suggested studying the injection of large amounts of sulphur dioxide in the Earth's stratosphere (situated at ~15-50 km altitude). Sulphate aerosol would build up, subsequently reflecting part of the 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 to the injection of particulate matter (and in particular sulphate aerosols) into the stratosphere through volcanic eruptions. For example, the eruption of Mt. Pinatubo in 1991 caused a reduction of global average surface temperature that was recognizable for more than 2 years afterwards and reached a maximum of about 0.5 K (Dutton and Christy, 1992).

Several other geoengineering methods to manipulate the radiative budget of the Earth have been suggested, e.g., reducing the incoming solar radiation through space-borne reflectors at the Lagrangian point, modifying low level marine cloudiness via the injection of additional condensation nuclei (e.g. Bower et al., 2006), and modifying the surface albedo (Gaskill and Reese, 2003). Among the discussed methods aiming at the removal of CO_2 from the Earth system is the fertilization of the oceans with iron, which is intended to lead to higher marine productivity and subsequent carbon sequestration by sedimenting ocean biomass (e.g. Buesseler and Boyd, 2003).

Side effects of geoengineering solutions

All these suggestions have been criticized heavily, in particular as they try to cure the symptoms of global climate change and not its causes. In the case of engineering radiation it might be possible to limit global temperature increase, but acidification of oceans as a consequence of increasing CO_2 levels would not be stopped. Another problem is the long lifetime of atmospheric CO_2 that would make it necessary to sustain geoengineering for periods of hundreds to thousands of years if no other technical way to remove CO_2 from the atmosphere were to be found.

On the positive side, a part of the long-term perturbation of the carbon cycle might be suppressed by geoengineering if positive feedbacks between global warming and the carbon cycle are as important as suggested in the recent IPCC report. Through such feedback mechanisms, the CO_2 concentration might actually be reduced by geoengineering. However, it is also possible that other, as yet uncharacterised feedbacks could result in an increase in CO_2 as a result of geoengineering. Substantial scientific research is needed to better understand such feedbacks.

Political and psychological concern exists that considering geoengineering might distract or prevent people from studying and investing in options to reduce the emission of GHGs, while they are expecting a geoengineering solution to climate change problems. The possibly enormous costs related to geoengineering options might well be better invested at an early stage in limiting GHG emissions.

Cicerone (2006) proposed an increase in scientific research on geoengineering to analyse expected side effects and search for unexpected ones. Additional stratospheric sulphur, e.g., might have a detrimental effect on the ozone layer. Bengtsson (2006), on the other hand, has raised concern about inaccuracies of current numerical Earth systems models that limit our capability to predict climate and to adequately study the consequences of geoengineering. Nevertheless, climate models are presently the only tools available for studying the climate evolution of the future under different emission and geoengineering scenarios, and as pointed out in the same issue (Lawrence, 2006), “if we do not conduct careful research now, we will not be prepared to advise politicians on how to best approach large-scale geoengineering applications – including providing sound information on the various risks involved, and on which ideas should not be pursued further”.

2.2 Specific scientific and technical objectives of the proposal

Given the amplitude of the current discussion on novel options to limit climate change, it is necessary to study the possible efficiency, risks and implications related to these options. Numerical models are the only possible tool for performing such initial scientific studies, since without further information, any large-scale experiments on the atmosphere would raise serious ethical concerns. The IMPLICC consortium proposed to perform model studies for three suggested options to engineer solar radiation. The focus was on

a) space borne reflectors (placed at the Lagrangian point between the Earth and sun),

b) sulphur injections into the stratosphere, and

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

Before IMPLICC, such studies had only been performed with numerical models that are too simplified to assess important possible risks. The IMPLICC approach was to use state-of-the-art Earth system models that (in particular) incorporate interactions between aerosols, radiation, clouds, air chemistry, the terrestrial biosphere, and the carbon cycle. Because of the limits and uncertainties of numerical models (as pointed out by Bengtsson, 2006), it was proposed to perform numerical studies in a multi-model setup where differences between the models can be taken as a first estimate of the uncertainty of the results. It was planned to base the simulations on climate change scenarios prepared for the fifth assessment report of the IPCC.

The objectives concerning the three methods mentioned above were to estimate their effectiveness and their side effects, and to contribute finally to a better understanding of their economic, legal, and ethical implications.

Specifically, IMPLICC was designed to contribute to answering the following questions:

a) Effectiveness

- How can geoengineering be applied in an efficient way? (At which altitude and geographical location should sulphur be injected into the stratosphere? Where should additional condensation nuclei be injected into the troposphere?)
- What is the amount of geoengineering necessary to limit the future global average temperature increase to a given target level, e.g., a maximum of 2 degrees?
- What is the radiative forcing efficiency (per mass emitted) and global "cooling" potential of the different substances suggested for geoengineering? What are the associated indirect radiative effects? Will the forcing efficiency of a given substance be different in a different (future) climate (e.g. under future levels of GHGs)?
- How quickly can the effect of a given geoengineering method be reversed in case of undesirable side effects?

b) Side effects

- How will stratospheric ozone levels and their future evolution be affected by stratospheric sulphur injections?
- What are the effects of a massive input of sulphur or chlorine species on tropospheric chemistry (acid rain, photo oxidant levels)?
- What are the spatial effects of eventually inhomogeneous manipulation of the radiative budget on hydrology (evaporation and precipitation patterns) and the terrestrial biosphere?
- What is the effect of an increase in diffuse radiation due to higher aerosol loads on vegetation?
- How do other photochemical processes in the troposphere and stratosphere change in response to the introduction of a given geoengineering substance (e.g., changes in photolysis rates, decreases in N_2O and CH_4, changes in UV flux due to the presence of SO_2)?
- Can we identify any unexpected significant changes in the climate system in the course of the continued application of geoengineering methods together with high GHG levels?
- What are the risks associated with a sudden switch-off of geoengineering (e.g., overshooting)?

c) Economic implications

- Based on the present state of knowledge, what are the ranges of costs for implementing geoengineering technologies?

- How are the benefits in terms of reduced climate change distributed across world regions, and what are the uncertainties about these benefits?
- How do the benefits and costs of geoengineering compare with the costs and benefits of emissions control?

Based on preliminary estimates of effectiveness it was planned to define numerical climate model experiments to assess climate effects and side effects of the techniques. Results of these experiments were intended as input for the economic analysis to answer the questions listed under c), and to be analyzed with respect to the remaining questions concerning effectiveness and side effects.

It was, however, clear from the start of IMPLICC that not only scientific and economic aspects are related to geoengineering, but also legal, political, and ethical issues. Properly addressing these questions was beyond the capabilities of this consortium. Instead, the main objective with respect to these issues was to foster their discussion.

2.3 Development of the context and objectives since 2009

The timeliness of the IMPLICC project is evident given the development of the scientific and societal interest in the topic of climate engineering since 2009. One clear evidence for the interest in the subject is the number of CE assessments published in the last three years and aimed at the broader public and decision makers. To our knowledge, the first such report was published by the UK Royal Academy ("Geoengineering the climate: science, governance and uncertainty", Shepherd et al., 2009), followed, e.g. by a study commissioned by the German ministry of education and science ("Large-Scale Intentional Interventions into the Climate System? – Assessing the Climate Engineering Debate", Rickels et al., 2011), and a "Technology assessment: Climate Engineering" (GAO, 2011) by the US Government Accountability Office.

The IMPLICC strategy of a model intercomparison study to identify potential robust results has received interest in a broader community beyond just the IMPLICC partners. Our project has been instrumental in the development of the internationally coordinated GeoMIP activity (Kravitz et al., 2011), and the IMPLICC partners are still contributing strongly to GeoMIP also beyond the end of the project. The numerical scenarios developed jointly for IMPLICC and GeoMIP are based on the climate change scenarios simulated in the context of the CMIP5 model intercomparison activity (Taylor et al., 2011) for the fifth assessment report (AR5) of the IPCC that will be published in 2013, and where, to our knowledge, IMPLICC results will be included.

Scientific research concerning climate engineering has made considerable progress during the last three years at many other research centers. However, none of the main IMPLICC objectives needed to be re-designed in the light of new knowledge. The analysis of the numerical simulations focussed, however, slightly stronger than maybe intended originally on the question how an engineered climate would look like, as it became more and more obvious during the course of the project that solar radiation management may limit the global temperature increase but not at the same time exactly restore a historical climate.

3. Description of the main scientific results/foregrounds

This report will concentrate on results obtained during the second reporting period of the project (months 19 to 39). Results of the first reporting period will be mentioned only briefly where appropriate. For more details the reader is referred to the intermediate project for months 1 to 18 and to the individual reports of the specific work packages of IMPLICC: Report on effects and side effects of space-borne reflectors (Deliverable D2.3), Report on the effects and side effects of deliberate injection of sulphur containing substances into the atmosphere (D3.3), Report on the effects and side effects of deliberate injection of sea salt into the atmosphere (D4.4), Final report on economic implications (D5.2).

3.1 The scientific approach

Table 1*: Main characteristics of the ESMs participitating in the model intercomparison studies. The first three models are IMPLICC models. Results from the HadGEM2-ES are included in the analysis of the G1 scenario of section 3.2.Table taken from Schmidt et al. (2012).*

Name of the ESM reference	IPSL-CM5A Dufresne et al. (2012)	MPI-ESM Giorgetta et al. (2012)	NorESM Alterskjær et al. (2012)	HadGEM2-ES Collins et al. (2011)
Atmosphere model (resolution; lid) reference	LMDz (2.5° × 3.75°/L39; 65 km) Hourdin et al. (2011)	ECHAM6 (T63/L47; 0.01 hPa) Stevens et al. (2012)	CAM-Oslo (based on CAM4) (1.9° × 2.5°/L26; 2 hPa) Seland et al. (2008)	HADGEM2-A (1.25° × 1.875°/L38; 40 km) The HadGEM2 Development Team (2011)
Ocean model (resolution) reference	NEMO (96x95 gridpoints, L39) Madec (2008)	MPIOM (∼1.5°, L40) Marsland et al. (2003)	(based on) MICOM (∼1°, L70) Assmann et al. (2010)	HadGEM2-O (1/3 to 1°, L40) The HadGEM2 Development Team (2011)
Land/Vegetation model reference	ORCHIDEE Krinner et al. (2005)	JSBACH Raddatz et al. (2007)	CLM4 Oleson et al. (2010)	MOSES-II Essery et al. (2003)

"LXX": XX indicates the number of vertical layers; "TYY": triangular truncation at wavenumber YY.

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.

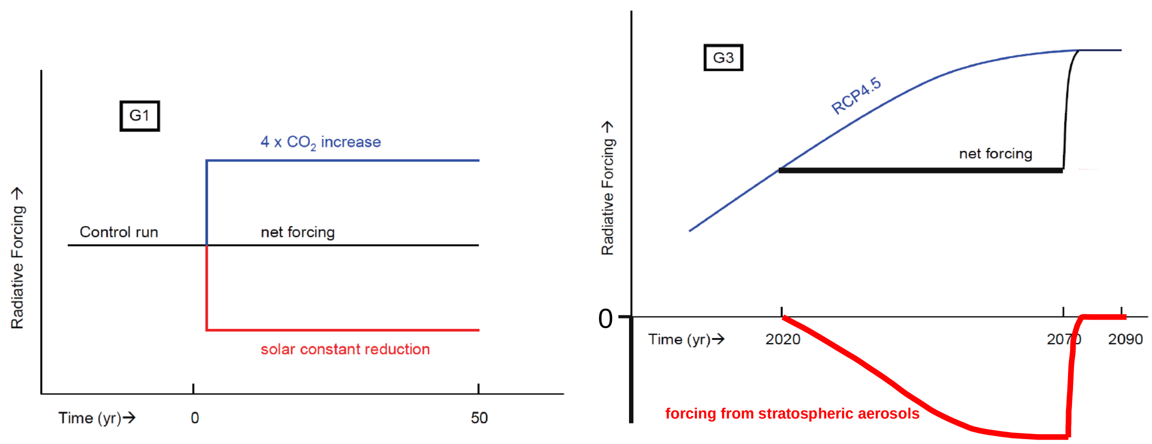


Figure 1*: Simulation strategies in the GeoMIP/IMPLICC numerical experiments G1 and G3. Figures are adapted from Kravitz et al. (2011). The simulation strategy for experiment G5 is identical to G3 except for the solar radiation management being realized via a manipulation of marine clouds through sea salt emissions and not through stratospheric aerosols.*

3.2 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 (Fig. 1) of IMPLICC/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 as can be seen from Fig. 2. 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.

***Table 2**: Comparison of multi-model mean responses to the forcings in G1 and abrupt4xCO2 simulations, respectively, with respect to piControl. Responses are calculated for the individual models both in terms of spatially averaged differences and in terms of root mean square differences, and then averaged over the four ESMs. RMS differences are calculated after interpolation of the results from the individual models to a 192x96 grid. Besides global mean values also averages over land surface only are provided. Table from Schmidt et al. (2012).*

	SAT (K)		Precipitation (mm day^{-1})	
	G1	4xCO2	G1	4xCO2
global average	0.1	5.5	−0.14	0.25
(percentage)			(−4.7 %)	(8.8 %)
land average	0.4	7.5	−0.12	0.16
(percentage)			(−6.3 %)	(8.3 %)
rms (global)	0.5	6.1	0.35	0.91
(percentage)			(12.2 %)	(31.6 %)
rms (land)	0.7	7.7	0.31	0.68
(percentage)			(16.4 %)	(36.4 %)

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

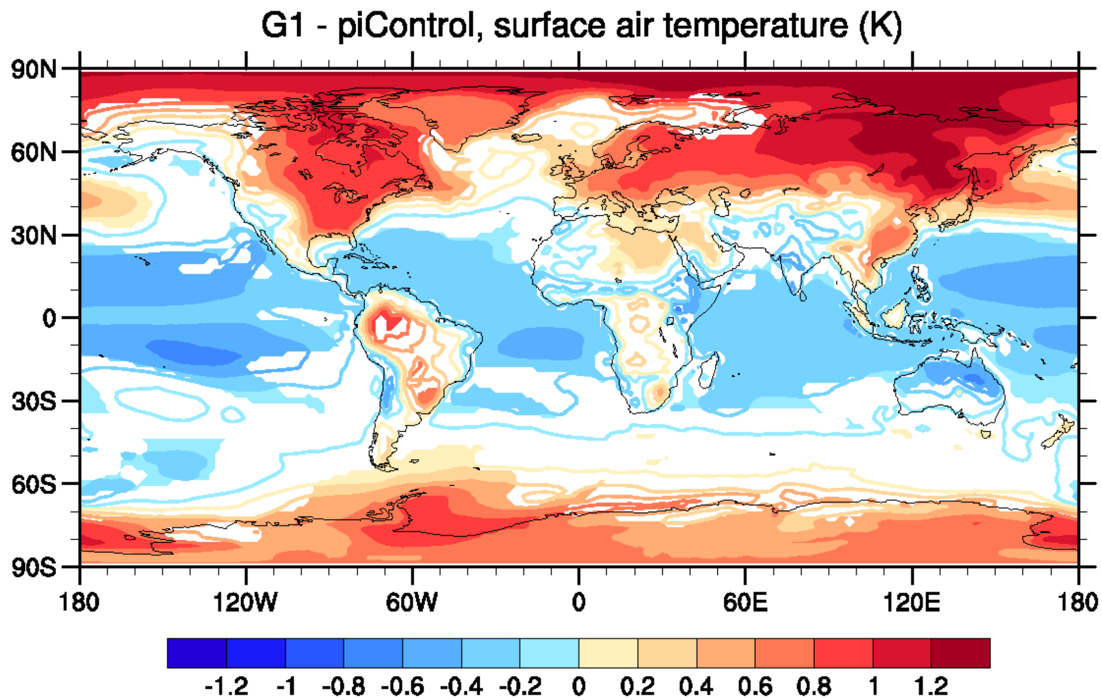


***Figure 2**: Differences in near surface air temperature (K) between the simulations G1 (with climate engineering) and the preindustrial control run, averaged over the four ESMs. In regions with filled colour shading all models agree in the sign of the response.*

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. 3).

Table 2 presents multi-model average responses in near-surface air temperature and precipitation from both scenarios (G1 and abrupt4xCO2) in terms of both mean and root mean square (rms) differences. Additionally, not only global means but also averages over all land surfaces are presented. It should be noted that the abrupt4xCO2 simulation is still not in equilibrium during years 101 to 150 which are used here. Table 2 shows that in both scenarios the temperatures over land areas increase stronger than in the global mean, but in the case of G1 the average temperature response over land is small (0.4 K). When expressed as rms differences multi-model mean changes of SAT under G1 are about an order of magnitude smaller than under abrupt4xCO2. This is true for both land and global mean responses. Table 5 confirms that global mean precipitation is much less balanced through the reduction of solar irradiance than temperature but the increase through increased GHGs is overcompensated in G1. The magnitude of precipitation responses in the two scenarios is in particular similar when only land masses are consideredonly (-6.3% in G1, vs. 8.3% in abrupt4xCO2). In terms of rms differences the CE in G1 reduces the precipitation anomalies caused in abrupt4xCO2 by a factor of 2.6 in the global mean and 2.2 over land surfaces.

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).

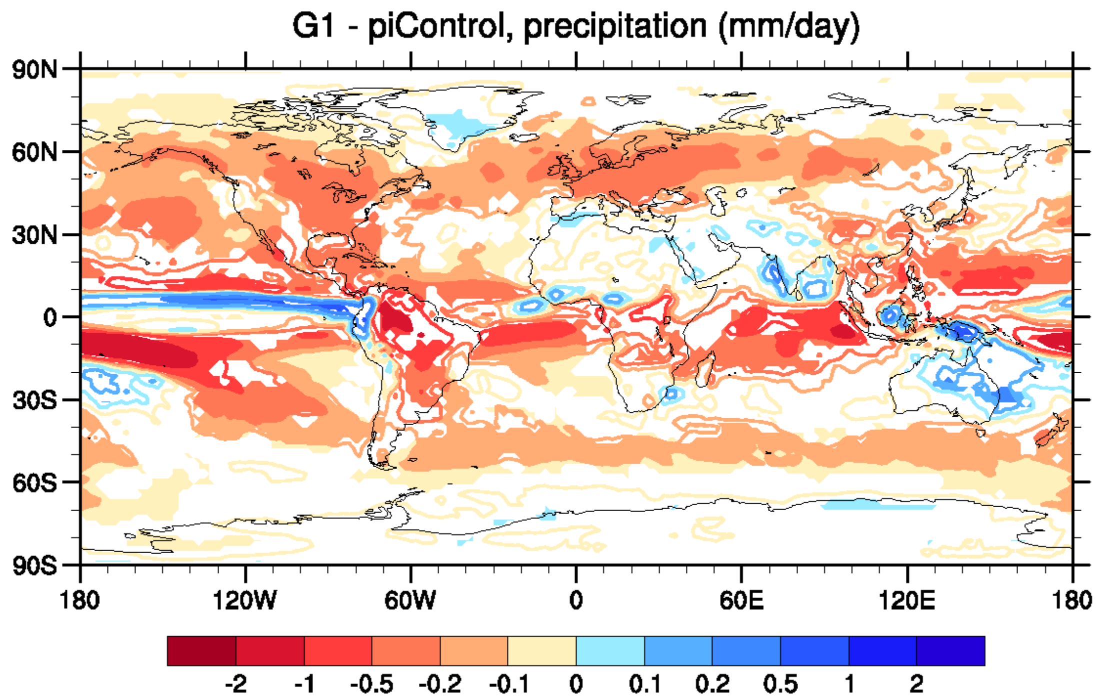


Figure 3: *Differences in precipitation (mm/day) between the simulations G1 (with climate engineering) and the preindustrial control run, averaged over the four ESMs. In regions with filled colour shading all models agree in the sign of the response.*

3.3 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.

3.3.1 Microphysical implications to the effectiveness of the injection of sulfur particles

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 although sedimentation plays only a secondary role in determining the aerosol residence time in the stratosphere, it does have an important role in the vertical distribution of the aerosol in the stratosphere as given by particle size. For that reason, a numerically diffusive scheme may considerably overestimate the vertical ascent of larger particles in the stratosphere, and thus, in conjunction with particle evaporation, lead to an underestimation of the total geoengineered aerosol load. Because of the deficiencies of existing sedimentation schemes, a new scheme with very low numerical diffusivity has been developed, implemented in the model and then used in the numerical experiments.

Furthermore, 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, and finally with respect to their radiative effects (Fig. 4). 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.

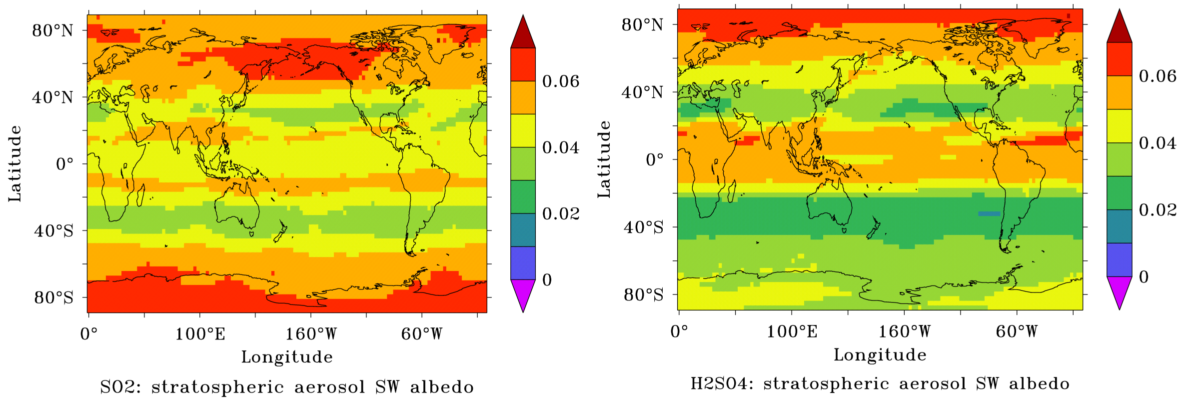


Figure 4*: Shortwave zenithal albedo of the geoengineered stratospheric aerosol layer obtained with the methods of SO2 release (left) and H2SO4 release (right). The height of injection is 25 km in a circumequatorial band, reaching from 10°S to 10°N. The mass injected per year is equivalent to 2 Mt S. Mass injection was started on Oct 1 2000. Results averaged for Jan 2004.*

3.3.2 Ozone effects of the injection of sulfur

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.

3.3.3 Climate effects of the injection of sulfur

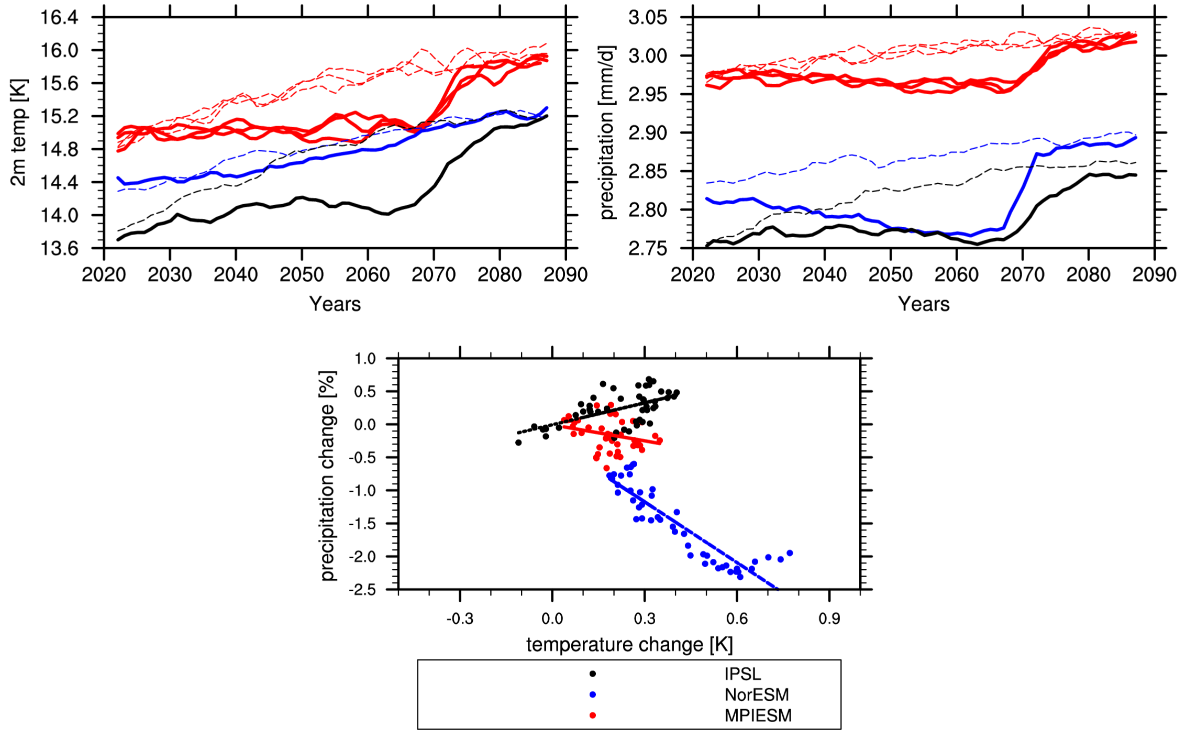


Figure 5: *Time series of globally and annually averaged data of three different ESMs (IPSL-ESM (black), Nor-ESM (blue), MPI-ESM (red)) for temperature near surface (top, left), precipitation (top, right) and hydrological sensitivity compared to climate averaged around year 2020 (bottom). The dotted lines are results of the RCP4.5 simulations.*

Potential climate effects of sulfur injections have been studied by comparing results from the three IMPLICC ESMs for the G3 scenario described in Section 3.1. Figure 5 shows time-series of annually averaged data of all simulations. With the MPI-ESM, a small ensemble of three simulations was performed, while the other two ESMs have performed single simulations. Results of MPI-ESM show only very slightly increasing near surface temperature. Nor-ESM shows a steady increase in temperature, as the amount of emitted sulphur was apparently too low to prevent the temperature form continuing to rise (but seems to have a strong impact on the precipitation), while IPSL-ESM shows increasing temperature until about 2050 and then a levelling-off or even slight decrease. As expected from the design of the numerical experiments, in all models, 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 in the MPI-ESM and IPSL-CM5A slightly and in the NorESM strongly reduced in 2070 compared to 2020. This can also be seen in the hydrological sensitivity, expressed as annual mean precipitation change over temperature change relative to CLIM2020 in the bottom panel of Fig. 5. Under non-CE climate change conditions, this sensitivity is of about 2% precipitation increase per Kelvin temperature increase (Held and Soden, 2006), but according to our results much smaller or even negative under CE. Concerning the regional patterns of precipitation response 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 is balanced by SRM. Balancing a larger forcing may lead to much stronger climate responses as discussed in

Section 3.2. 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 bring back the global mean temperature 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 3.5.

3.4 Implications of CE through the manipulation of marine clouds

It has been known for more than 30 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.

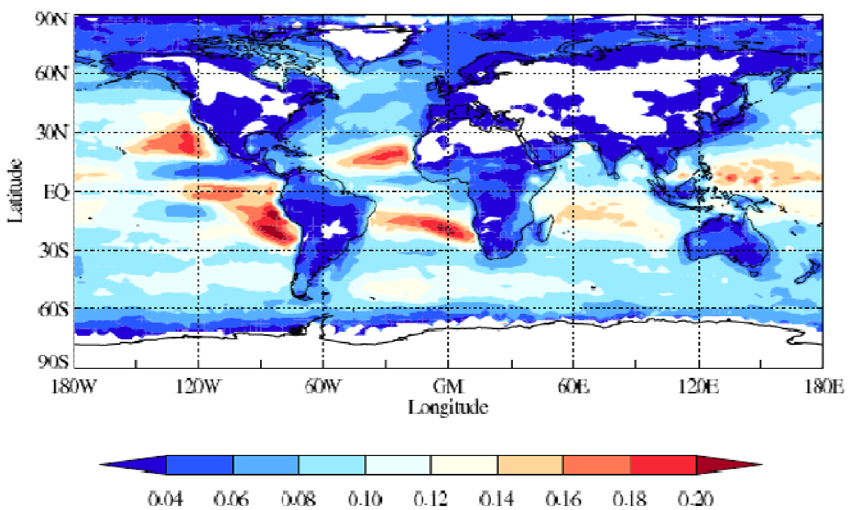


Figure 6: *Total susceptibility function from a 5-year simulation with the NorESM model. The larger the value of this function is, the better suited is the respective area for climate engineering through sea salt emissions.*

3.4.1 Microphysical implications of sea salt emissions

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^{o}N and 30^{o}S, in particular off the west coasts of the continents (Fig. 6). 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. 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.

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.

3.4.2 Climate effects of the manipulation of marine clouds

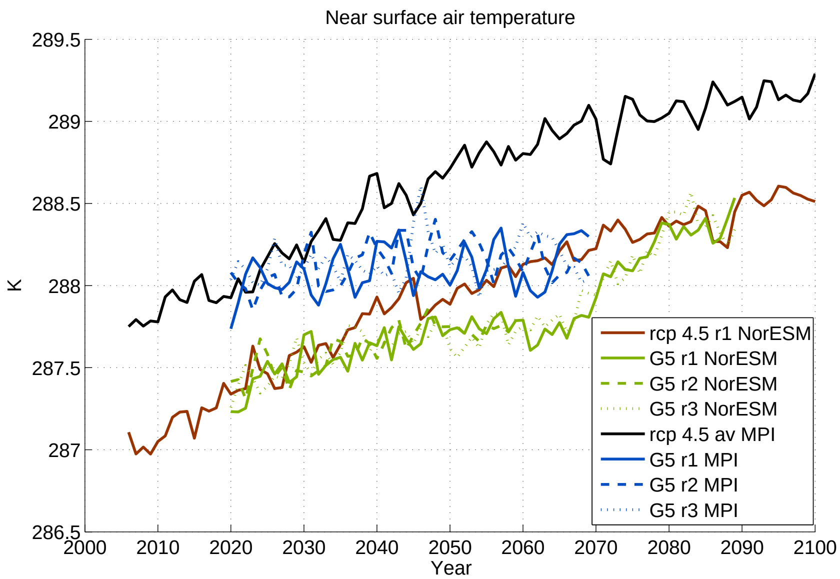


Figure 7: *Evolution of the globally averaged near-surface temperature in simulations with the MPI and NorESM models. The black (MPI) and red (NorESM) curves represent the RCP4.5 scenario runs, while the three blue curves (MPI) and the three green curves (NorESM) are the simulations with marine cloud brightening applied from 2020 to 2069. In NorESM the simulations were continued for another 20 years (through 2089) after geoengineering was switched off, while the MPI runs terminate at 2069.*

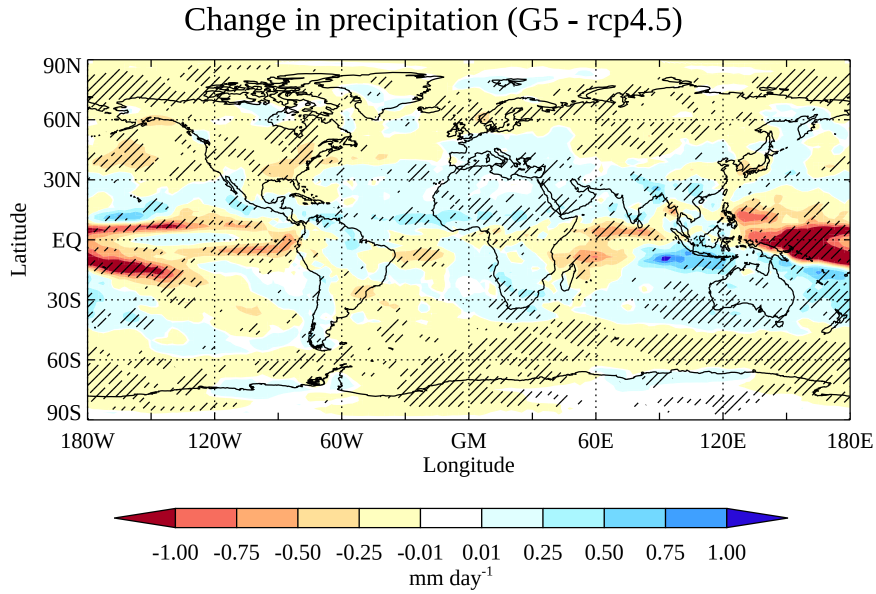


Figure 8*: Simulated difference in precipitation at years 2060-2069 between the G5 simulation and the RCP4.5 simulation. The figure shows the average result for both the MPI-ESM and NorESM models. Hatching indicates regions where all the five simulations (three realizations with MPI-ESM, two with NorESM) agree on the sign of the difference.*

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 (Fig. 7), 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 (Fig. 8).

3.5 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. 9 (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°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. 9 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

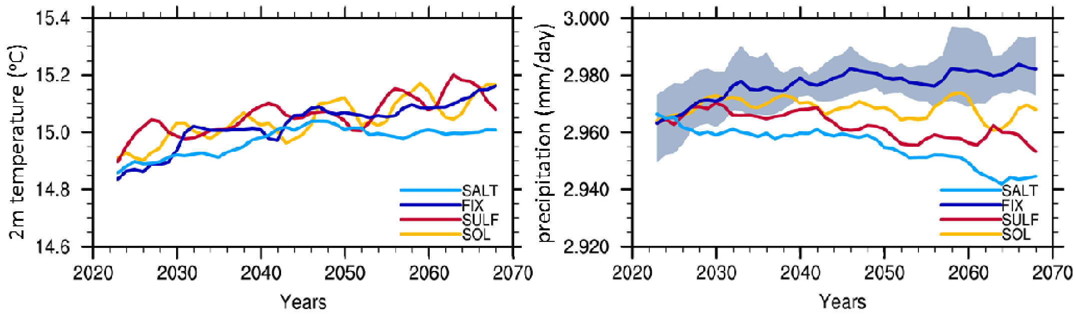


Figure 9*: Time evolution of global mean temperature (^oC, left) and precipitation (mm/day, right) simulated with the MPI-ESM under four different scenarios of type G3, i.e. where it is attempted to keep the climate forcing constant at 2020 levels through different methods. SALT: manipulation of marine 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.*

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 3.2) 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.

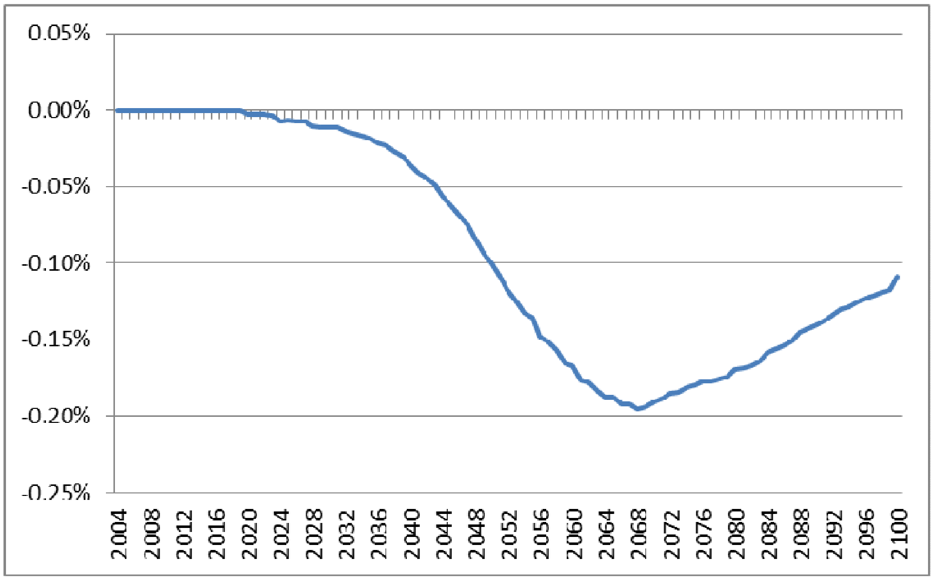
3.6 Economic Implications of CE

The numerical economic general equilibrium model GRACE (operated by CICERO) was used to estimate economic implications of the IMPLICC climate engineering scenarios. The model is a global computable general equilibrium model, which uses the GTAP version 7 social accounting matrices (Badri and Walmsley, 2008). It is built up with CES aggregates in both production and consumption, and trade between regions is represented by Armington functions (Aaheim and Rive, 2007). Investments, population and technological developments are exogenous, while impacts of climate change are attached to the relevant factor of production in each case (Aaheim and Schjolden, 2004). For example, impacts to the productivity of land in agriculture are expressed as a reduction in the availability of natural resources in the sector. One sector may thereby be affected by more than one impact, such as productivity of land, extreme events, which affects the capital stock (and possibly land) and health effects, which affect labour supply. Climate change thereby gives rise to factor substitution as well as sector substitution, which is interpreted as autonomous adaptation. The model divides the world into 11 regions and 15 economic sectors, shown in Table 3.

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 CO2-emissions, and the SRM scenarios G3 using sulfur emissions (as discussed in Sections 3.3) to further limit the climate change experienced under RCP4.5. Climate change information as calculated by the IMPLICC-ESMs was used in the economic model.

Table 3*: Economic sectors and regions in GRACE.*

<table>
<tr><th rowspan="2">Sectors</th><th colspan="3">Regions</th></tr>
<tr><th>Name</th><th>Abbr.</th><th>Comprises</th></tr>
<tr><td rowspan="11">Agriculture
Forestry
Fisheries
Crude oil
Coal
Refined oil
Electricity
Gas
Iron and steel
Non-metallic minerals
Other manufacturing
Air transport
Sea transport
Other transport
Services</td><td>Western Europe</td><td>WEU</td><td>EU15, Nordic, Iberia and Greece</td></tr>
<tr><td>Central and Eastern Europe</td><td>CEE</td><td>Sovereign countries of the former Warsaw pact plus Baltic states and former Jugoslavia</td></tr>
<tr><td>Former Soviet Union</td><td>FSU</td><td>Other former Soviet states</td></tr>
<tr><td>Mdl East & North Africa</td><td>MSA</td><td>Mediterranian Africa, and countries in the triangle Turkey – Saudi Aarabia – Iran</td></tr>
<tr><td>Sub-Saharan Africa</td><td>AFR</td><td>States in Sahara and southern Africa</td></tr>
<tr><td>South Asia</td><td>SAS</td><td>Afghanistan, Pakistan, India, Nepal, Bangladesh, Nepal, Maldives, Bhutan</td></tr>
<tr><td>East Asia</td><td>EAS</td><td>China, Mongolia, North Korea</td></tr>
<tr><td>Other Pacific Asia</td><td>PAS</td><td>Asian peninsula and island states</td></tr>
<tr><td>Pacific OECD</td><td>PAO</td><td>Japan, South Korea, Australia, New Zealand</td></tr>
<tr><td>North America</td><td>NAM</td><td>USA and Canada</td></tr>
<tr><td>Latin America</td><td>LAM</td><td>Carribbean, Mexico and further south</td></tr>
</table>



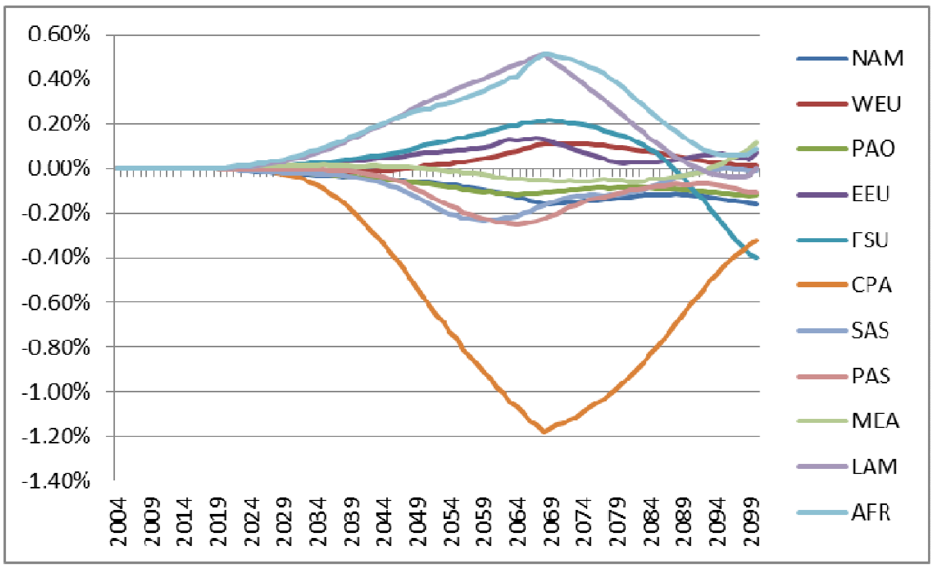


Figure 10*: Impact on world's GDP of SO2 injection relative to GDP in RCP4.5 based on climate change calculated in the RCP4.5 and G3 scenarios with the MPI-ESM. Top: global average; bottom: averages for different regions as defined in Table 3.*

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 benefits of further reducing radiative forcing by solar radiation management are negative in the G3 scenario (Fig. 10, top). 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 (Fig. 10, bottom). 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 may become 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.

3.7 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 climate engineering under a moderate emission 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.

4. Potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

The goal of IMPLICC was not to develop new approaches or technologies, but rather to increase the level of knowledge about the feasibility and implications of existing suggestions to engineer the climate through solar radiation management (SRM). A better understanding of effectiveness and potential side effects (as on the hydrological cycle, see above) of suggested SRM methods is crucial in order to allow for an information-based decision making.

In this respect we were in particular interested in the question what climate would result from SRM. Given that climate model results are uncertain due to the imperfectness of the models and different choices of e.g. parameterizations or numerical approaches may lead to different results, it was a key element to perform a standardized set of numerical SRM scenarios with different stat-of-the-art climate models. IMPLICC not only gathered three European models for this purpose but was, beyond the original proposal, also instrumental in setting up a larger international effort (GeoMIP, Kravitz et al., 2011, http://climate.envsci.rutgers.edu/GeoMIP/index.html) that is ongoing. Some of the proposed numerical experiments have now been performed by more than ten climate models from centers in Europe, North America and Asia and are currently being analyzed.

A key result of IMPLICC (Schmidt et al., 2012) obtained through a comparison of results from four models is improved knowledge on the response of the hydrological cycle to SRM. It was already known that likely SRM would over-compensate the global mean precipitation increase from increased greenhouse gases, i.e. a geoengineered climate would have less precipitation than a natural climate of the same global mean temperature. It is concluded in this paper that the potentially strong climate responses of SRM 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.

In particular this publication had a strong media echo, partly triggered by the decision of the European Geosciences Union to accompany the publication by a press release (http://www.egu.eu/news/4/geoengineering-could-disrupt-rainfall patterns/). Results of the study have been reported by likely more than 30 print and online media and in radio interviews in several European countries. Total media coverage of IMPLICC results is significantly higher. Additionally, many members of the IMPLICC consortium have interacted with the public in particular in the form of public lectures (for instance at schools) or in public panel discussions. Results of IMPLICC have contributed significantly to the compilation of a brochure on climate engineering by the Max Planck Society that is distributed to schools for the use in classes (http://www.max-wissen.de/Fachwissen/show/0/Heft/Geo-Engineering.html). Finally, deliverable 6.3, the "Synthesis report for policy makers and the interested public" is trying to inform the public about the outcome of the project. This deliverable is available via the project website http://implicc.zmaw.de).

The dissemination of IMPLICC results in the scientific community is ongoing. However, already four peer-reviewed publications of IMPLICC results have appeared, and results have been presented in numerous presentations (often invited) on scientific meetings and congresses and at scientific institutes, world-wide. To our knowledge, results obtained within IMPLICC will also be covered in the fifth assessment report (AR5) of the IPCC that will be published in 2013.

5. Project website and other contact details

Important information on the IMPLICC project has been posted on the project's public website http://implicc.zmaw.de. In particular the list of publications resulting from the work within the project will also be updated in the future.

For specific information on the work within the project and related activities we further recommend to contact the coordinator of the project or the work package leaders:

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References (related to the IMPLICC project)

Alterskjær, K., & Kristjánsson, J. E. (2012), The sign of the radiative forcing from marine cloud brightening depends on both particle size and injection amount, submitted to Geophys. Res. Lett.

Alterskjær, K., Kristjánsson, J. E., & Seland, Ø. (2012), Sensitivity to deliberate sea salt seeding of marine clouds-observations and model simulations. Atmospheric Chemistry & Physics, 12, 2795-2807.

Benduhn, F., and Lawrence, M.G. (2012), New Aerosol Sedimentation Schemes with Low Numerical Diffusion: A Sensitivity Study on the Relevance of Sedimentation for Stratospheric Climate Engineering, submitted to J. Geophys. Res..

Kravitz, B., A. Robock, O. Boucher, H. Schmidt, K. E. Taylor, G. Stenchikov, and M. Schulz (2011), The geoengineering model intercomparison project (GeoMIP), Atmospheric Science Letters, 12, 162-167, doi:10.1002/asl.316.

Niemeier, U., H. Schmidt, and C. Timmreck (2011), The dependency of geoengineered sulfate aerosol on the emission strategy, Atmospheric Science Letters, doi: 10.1002/asl.304.

Schmidt, H., K. Alterskjær, D. Bou Karam, O. Boucher, A. Jones, J. E. Kristjánsson, U. Niemeier, M. Schulz, A. Aaheim, F. Benduhn, M. Lawrence, and C. Timmreck (2012), Solar irradiance reduction to counteract radiative forcing from a quadrupling of CO_2: Climate responses simulated by four Earth system models, Earth Syst. Dynam., 3, 63-78.

References (unrelated to IMPLICC)

Aaheim, A., A. Schjolden (2004): “An approach to utilise climate change impacts studies in national assessments”, *Global Environmental Change***,** 14, 147-160.

Aaheim, A., N. Rive (2005): “A model for Global Responses to Anthropogenic Changes in the Environment (GRACE)”, *CICERO Report* 2005:5, CICERO, Oslo.

Badri, N. G., & Walmsley, T. L. (2008). Global trade, assistance, and production: The GTAP 7 data base. *Center for Global Trade Analysis, Purdue University*.

Bengtsson, L., (2006), Geo-engineering to confine climate change: Is it at all feasible? Climatic change, 77, 229-234.

Bower, K., T. Choularton, J. Latham, J. Sahraei, S. Salter (2006), Computational assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds. Atm. Res., 82, 328-336.

Buesseler, K. O. and P. W. Boyd (2003), Will ocean fertilization work? Science, 300 (5616), 67-68.

Crutzen, P. J. (2006), Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? Climatic Change, 77, 211-220.

Dufresne J-L, Foujols, M-A, Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., de Noblet, N., Duvel, J-P., Eth´e, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J-Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M-P., Lefevre, F., Levy, C., Li, Z. X.., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., ,Szopa, S., Talandier, C., Terray, P., Viovy, N., Climate change projections using the IPSL-CM5 Earth System Model: fromCMIP3 to CMIP5, J Clim Dyn., in revision, 2012.

Dutton, E. G., and J. R. Christy (1992), Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruptions of El Chichòn and Pinatubo, Geophys. Res. Lett., 19, 2313-2316.

GAO: Technology asessment: Climate Engineering: Technical status, future directions and potential responses, US Government Accountability Office, Washington, USA, 2011.

Gaskill, A. Jr. and C.E. Reese (2003), Global Warming Mitigation by Reduction of Outgoing Longwave Radiation Through Large-Scale Surface Albedo Enhancement of Deserts Using White Plastic Polyethylene Film-the Global Albedo Enhancement Project (GAEP) Research Plan, Report from Environmental Reference Materials, Inc., Research Triangle Park, NC, USA.

Heckendorn, P., Weisenstein, D., Fueglistaler, S., Luo, B. P., Rozanov, E., Schraner, M., ... & Peter, T. (2009). The impact of geoengineering aerosols on stratospheric temperature and ozone. *Environmental Research Letters*, *4*(4), 045108.

Held, I. M., & Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climate*, *19*(21), 5686-5699.

Hourdin, F., Foujols, M.-A., Codron, F., Guemas, V., Dufresne, J.- L., Bony, S., Denvil, S., Guez, L., Lott, F., Ghattas, J., Braconnot, P., Marti, O., Meurdesoif, Y., and Bopp, L.: Impact of the LMDZ atmospheric grid configuration on the climate and sensitivity of the IPSL-CM5A coupled model, Clim. Dynam., in press, 2012.

IPCC (2007a), Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007b), Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 7-22.

Krinner, G., Viovy, N., de Noblet-Ducoudr´e, N., Og´ee, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cy., 19, GB1015, doi:10.1029/2003GB002199, 2005.

Lawrence, M. (2006), The geoengineering dilemma: to speak or not to speak, Climatic change, 77, 245-248.

Madec, G.: NEMO ocean engine, Tech. Rep. 27, Institut Pierre Simon Laplace des Sciences de l'Environnement Global, Paris, France, 2008.

Rickels, W., Klepper, G., Dovern, J., Betz, G., Brachatzek, N., Cacean, S., Gussow, K., Heintzenberg, J., Hiller, S., Hoose, C., Leisner, T., Oschlies, A., Platt, U., Proelss, A., Renn, O., Schafer, S., and Zurn, M.: Large-Scale Intentional Interventions into the Climate System? – Assessing the Climate Engineering Debate. Scoping report conducted on behalf of the German Federal Ministry of Education and Research (BMBF), Kiel Earth Institute, Kiel, Germany, 2011.

Schneider, S. H. (2001), Earth systems engineering and management, Nature, , 417–421.

Shepherd, J., Caldeira, K., Cox, P., Haigh, J., Keith, D., Launder, D., Mace, G., MacKerron, G., Pyle, J., Rayner, S., Redgwell, C., and Watson, A.: Geoengineering the Climate: Science, Governance and Uncertainty, The Royal Society, London, UK, 2009.

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society, 93*(4), 485.