CLIMATE ENGINEERING ?

Risks, Challenges, Opportunities?

Modelling in Climate Engineering Research

Significance and Uncertainties

Priority Programme 1689 of the German Research Foundation DFG

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This is a translation of the german brochure
“Modellierung in der Climate Engineering Forschung –
Aussagekräftig trotz Unsicherheiten”.

Preface

In the priority programme "Climate Engineering: Risks, Challenges, Opportunities?" (SPP 1689), we want to provide a comprehensive evaluation of the ideas that have emerged on Climate Engineering (CE) in science and climate politics in recent years. CE is the term used to describe deliberate large-scale interventions in the climate system, with the aim of mitigating the effects of climate change caused by humans. For a robust assessment of CE ideas, we take into consideration the social, political, legal and ethical aspects, in addition to the scientific and technical dimensions. The results are also discussed within the context of mitigation and adaptation strategies for climate change. Our research to assess (not develop!) CE deliberately takes a very broad interdisciplinary approach. Field experiments are explicitly excluded within the context of the SPP 1689. The research is, therefore, extensively based upon the results of computer simulations with numeric models of the climate system.

In order to better understand the functioning, limits and opportunities of such models, the SPP PhD students from all involved disciplines organised a multi-day workshop on the topic of modelling under the direction of Miriam Ferrer González and Fabian Reith, together with the project coordinator Ulrike Bernitt. The questions, discussions and ideas which emerged during this workshop prompted us to summarise in writing the different aspects of modelling within the context of our priority programme for the evaluation of CE. In addition to the participants of the workshop, other members of the SPP 1689 from various disciplines, such as the fields of philosophy and economics, have contributed. With the resulting brochure, we hope to inform both scientists and interested members of the public about the basic aspects of our research, thereby making it easier to join the discourse on CE.

ANDREAS OSCHLIES

CONTENT

The Role of Modelling in Climate Engineering Research
| Andreas Oschlies 3

How do Computer Simulations Influence Scientific Understanding?
| Martin Carrier and Johannes Lenhard 6

Dealing with Uncertainties
| Gregor Betz 9

Uncertainties in Numeric Climate Simulations in a Decision Context
| Hauke Schmidt and Hermann Held 12

The UVic Earth System Climate Model
| David Keller, Nadine Mengis, Fabian Reith and Andreas Oschlies 15

The MPI Earth System Model
| Sebastian Sonntag, Tatiana Ilyina, Julia Pongratz and Hauke Schmidt 18

The IPSL-CM Earth System Model
| Olivier Boucher, Ulrich Platt and Christoph Kleinschmitt 21

The Regional Model System COSMO-ART
| Tobias Schad, Thomas Leisner and Bernhard Vogel 24

The LPJmL Vegetation Model
| Tim Beringer, Lena Boysen and Vera Heck 27

Economic Modelling in the Context of Climate Engineering
| Timo Goeschl and Martin Quaas 30

Priority Programme 1689 33

Authors 34

Imprint | Contact 35

The Role of Modelling in Climate Engineering Research

Andreas Oschlies | Earth System Modelling

The term "Climate Engineering" (CE) covers various large-scale technical measures, which could be used in a targeted manner either to lower the concentration of atmospheric CO_2 or to directly influence the Earth's radiation balance in order to counteract anthropogenic global warming. The CE methods discussed within the research community and in the public have, until now, only been ideas for technical methods that initially appear plausible and could in principle work. On the other hand, however, it is difficult to examine their actual effectiveness and assess unintentional side effects. As CE methods would be a targeted intervention in the climate system, which is a globally connected system of high complexity that is not yet sufficiently understood. Under laboratory conditions or during small-scale field experiments (e.g. iron fertilisation in the ocean or afforestation), the potential effectiveness and side effects of CE methods can only be tested in a very limited manner. It is also unclear to what extent the results of such small-scale and short-term experiments can be transferred to the global climate system.

In order to assess the global effects and side effects of CE in an empirically reliable manner, corresponding large-scale and possibly global field experiments would be required. However, these would perhaps not differ significantly from an actual deployment of CE and could involve considerable risks since the results of scientific experiments cannot be predicted with certainty. The consequences of such experiments carried out in the natural environment could be irreversible and the observed effects, in view of our incomplete understanding of the climate system, might not even be unambiguously attributable to the experiment. Furthermore, there is a lack of governance regarding the permission, supervision and regulation of field experiments (and also for the deployment of CE methods). In consideration of the uncertainties,

the considerable risks involved and the large parts of the population potentially affected, it is not currently possible to carry out large-scale CE field experiments in a responsible manner.

The opportunity to examine the effects and side effects of various CE methods without putting people or the environment at risk is provided by numeric models of the Earth system, which allow experiments to be carried out in a simulated world, rather than in the real natural environment. Earth system models simulate the interactions between various components of the climate system on the basis of scientific laws. These laws are presumably neither complete nor correct in every detail, which means that the simulated world is not a perfect copy of reality. Furthermore, the mathematical equations corresponding to the laws of science can often only be solved using numeric approximations (for example, the description of small-scale turbulence). The more exact the representation is, the higher the computational power required, which in practice generally limits the duration of a simulation.

Coupled models containing model components describing the ocean, sea ice and the atmosphere, are generally described as climate models. Earth system models also contain modules to describe terrestrial vegetation,

MODELLING

The description of a complex or real system through simplified mathematical formulations is called modeling. Generally these formulations are written and calculated using computer programs, with the results giving a simplified depiction of reality. A simulation describes the application of a particular model in a way that can be varied as desired. Simulated experiments allow us to gain an understanding of given questions, without having to actually conduct the experiments in nature. This enables us to make predictions, test hypotheses and illustrate causal relationships.

As simplified depictions, models will always be incomplete and must, therefore, not be thought of as reality, something that has to be considered when interpreting the results. However, because of these simplifications models are also important tools for understanding single processes in complex systems. How complex a model has to be depends on what questions are being asked.

soil, marine ecosystems and biogeochemical cycles. Different research groups and disciplines use different models. These models differ according to the research questions, their objectives and, depending on which components are to be represented, in their level of detail in the description of the different components.

Within the context of the SPP 1689, simulations using several different Earth system models of varying degrees of complexity deliver possible scenarios, by which all working groups of the SPP 1689 can orient themselves. They thereby also form a basis for the investigation of the potential effects of CE by the humanities or social sciences e.g. with regard to the model's epistemic value or the meaning of the modelling results in political discussions and decision-making processes. Even with this highly interdisciplinary approach, it must always remain clear that these models are only simplified representations of reality. They neglect to consider potentially important processes and include parameterizations[1] of unresolved processes. They also depend on often only poorly known initial and boundary conditions. Because of this, each model simulation contains uncertainties that must be taken into consideration when interpreting the results.

Despite these limitations on the validity of the models, in our view an assessment of the effectiveness and side effects of CE methods can currently only be carried out responsibly using computer simulations.

1 | Parameterizations are simplified descriptions of processes that are not fully described in the Earth system models (e.g. cloud development, turbulence and numerous biological processes).

How do Computer Simulations Influence Scientific Understanding?

Martin Carrier and Johannes Lenhard | Philosophy of Science

A rapidly growing number of scientific investigations rely on computer simulations. These include investigations into Climate Engineering (CE), which gives rise to questions on the methodological characteristics of computer simulations and their effects on our understanding of science.

What is special about computer simulations? They are based on theoretical, mathematically-formulated models, which are automatically processed by digital computers. This requires the conversion of the theoretical models into a form that can be dealt with by computers. For this purpose, differential equations, need to be solved in numerical form, that is, solutions have to be calculated point by point and for specific parameter values. Modelling of this type differs from conventional mathematical modelling with regard to methodology. The defined parameterizations and other adaptations, which are required due to the digitalisation of the models, are often not produced by the relevant theories but rather by independent modelling steps. Clouds, for example, can only be described in the simulation model by their effects at the grid points. One must, therefore, find a type of condensed description (parameterization), which works together with the remaining dynamics at the grid points in such a way that it adequately captures the main effects of the much more complicated and fine-scaled cloud formation processes.

The model dynamics are often significantly influenced by the way in which the parameterization is chosen and how the corresponding parameters are set. However there is no guaranteed recipe for success for this type of modelling step. The particular behaviour of the model is not derived from the theory alone, but also depends on the auxiliary

adjustments applied. Theory thereby loses part of its epistemic authority. The relationship between theoretical approach, pragmatic modifications and predictive value is not yet well understood with regard to its effects on understanding scientific modelling. Reflection on how computer simulations contribute to changing exploratory and explanatory procedures in science is still in its infancy.

Important is that computer simulations also deliver results for complex, specialised circumstances, for which an analytical solution is inconceivable. Simulations are, therefore, suited to spelling out the consequences of theoretical principles that would otherwise be inaccessible. Of course, in view of the mentioned concerns, it needs to be ensured that these consequences actually originate from the theoretical principles themselves, and not from the pragmatic adaptations of these principles for making them suitable for being run on digital computers. Are the claims made by the theoretical model actually determined by its theoretical principles or by the implementation of these principles for numeric simulation processes? Under what conditions can we therefore expect that our simulation models adequately represent the future climate development?

A fundamental way of assessing a model is checking it against experience. Such a test can be achieved by exploiting an advantage of simulation models related to the immense computational power of computers. Namely, one can use such simulation models experimentally. One changes certain parameters or procedures on a trial basis and examines the effects this has on verifiable consequences of the model. In this way, certain parameterizations and calculation procedures can be distinguished through experience. One is, therefore, not experimenting with nature but rather with the models. In such simulation experiments, models are tested and adapted, if so required, in order to be able to better judge their importance for specific questions. In this way, an experimental path is opened up to testing the validity of simulation models.

However, computer simulations face a specific problem with regard to validation. In areas such as CE, while theoretically well-confirmed conceptual models are available, the aim is precise, long-term predictions. Because these predictions refer to conditions that have not yet been realised, empirical validation of CE simulation models is difficult. However, support for these models on theoretical grounds is also problematic, because of the mentioned dependence of the results on parameterizations and auxiliary calculation procedures. We simply do not know exactly on which components of the model the specific predictions primarily rely. Accordingly, computer simulations also raise special problems for the validity testing of models.

Philosophers try to reconstruct the problems associated with such a validity test by tracing the conceptual structure of the models and analysing the relationships between their underlying theoretical assumptions and the empirical basis. Philosophy then strives to make the conceptual structure of the model and the corresponding validation relationships transparent. In addition to this reflection on the instruments of knowledge gain (instead of their construction and use, as is done by natural scientists), philosophers compare the relevant model characteristics to similar or dissimilar cases from other scientific disciplines or place these within the context of the historical development of science. This contextualisation may not only allow a deeper understanding of these specific characteristics, it may also provide a heuristic means of appropriately addressing problems in the validity testing of climate models.

Dealing with Uncertainties

Gregor Betz | Philosophy of Science

Quantitative modelling and computer simulations do not in general guarantee certainty or reliability. Model results can be more or less uncertain for various reasons: Relevant causal connections may not be identified by the model; the values of certain model parameters are poorly constrained; or the initial and boundary conditions are unknown.

We possess both linguistic and mathematical means to express uncertainty in a differentiated manner. In many cases, quantitative probabilities can be reliably determined. In other situations, only relevant possibilities can be identified, e.g. by giving an interval, an order of magnitude or a development trend for a variable.

It is disputed among both climate scientists and philosophers of science which type of knowledge is provided by climate models and how their (partly heterogeneous) results are to be interpreted. There are at least four suggestions for how to understand climate models and their outcomes:

1. One regards the models as competing hypotheses about the actual climate system and assumes, for practical purposes, the forecasts of the model which is empirically best confirmed.

2. One interprets the frequency distribution of the model results themselves as probability distribution in order to thus quantify the uncertainty associated with forecasts.

3. One interprets the model results as scenarios that cover the range of plausible possibilities.

4. One uses the models to identify previously unseen (not even articulated) consequences of actions (*unknown unknowns*).

What are the practical ramifications of model uncertainties? How is one to take these uncertainties into consideration when reflecting on and making decisions?

Whether a decision is right or wrong depends on the consequences associated with the various options of action. Forecasts of the consequences of actions are the central *descriptive assumptions*[2] in derivations of policy recommendations. Evaluations of Climate Engineering (CE) options hinge, for example, on the intended and unintended consequences of the research on, and the deployment of, CE technologies. Risk preferences and the evaluation of possible consequences represent the *normative assumptions*[2] that fuel such practical reasoning. It is therefore possible for two parties to agree on the forecast[3] and the evaluation of the consequences of policy options but, due to different levels of risk aversion, to disagree on the measure to be taken.

In risk ethics and decision theory, decision situations are classified according to the available foreknowledge, which can be more or less uncertain, namely as decisions

- under risk (probabilities can be assigned to possible consequences of actions)
- under uncertainty (all possible consequences of actions are identified)
- under ignorance (some relevant consequences of options are unknown)

2 | Descriptive assumptions describe what is (and/or was or will be) the case; normative assumptions say something about what should be the case and evaluate a situation without implying that it actually obtains. "Peter keeps his promises", for example, is a descriptive statement, "Peter should keep his promises" however is a normative statement.

3 | Probability forecast or possibility forecast.

It is in principle possible, in all these situations, to argue rationally for or against an action. In decisions under risk, the principle of expected utility maximisation is often used. In case proper uncertainty prevails, the precautionary principle can be applied.

Whether, in the context of CE, we face decision situations under risk or rather under uncertainty, crucially depends on how climate models and their results are interpreted.

Uncertainties in Numeric Climate Simulations in a Decision Context

Hauke Schmidt | Climate Science
and Hermann Held | Physics and Climate Economics

Numeric computer models of the Earth system are indispensable tools for estimating future climate development. The climate of the future is projected based on scenarios for future greenhouse gas emissions. How precise must such projections be?

The social relevance of the accuracy of climate projections is expressed among other things in the economic benefit that could emerge (because of the increased ability to plan at that point), if the projections could be more precise.

The expected benefit of maximum precision for scenarios without Climate Engineering (CE) has already been calculated: Globally, it lies somewhere between billions and hundreds of billions of Euro per year (for these results, it was simply assumed that any underdeterminedness of climate projections can be expressed through a probability distribution). Moreover, it makes sense to suggest that the strength of the reaction of the climate system to greenhouse gases plays a role in the assessment of whether the use of CE seems reasonable. The essential strategies for assessing the reliability of the climate model projections are a) evaluation of the models on the basis of observed data and b) comparison of different models.

Model evaluation:

In order to generate confidence in future projections of a model, a necessary condition is the realistic simulation of the observed climate development of the 20th century. This is not a guarantee for the correctness of the projections of the future though. Most models at large climate research centres, for example, reproduce the observed average global rise in temperature so far quite well. However, this does not necessarily mean that the underlying mechanisms are described

correctly in the models. For example, the quantification of the effect of anthropogenic atmospheric aerosols is uncertain. Possible errors by a model with regard to the effect of greenhouse gases on the temperature (climate sensitivity) could, therefore, be compensated by various ways of taking aerosol effects into consideration. Because of this, it is necessary to perform the evaluation using different parameters and not only the globally averaged temperature.

For simulations of CE methods, there is also the problem of the lack of experience and empirical evidence. For example, in the case of the CE suggestion to inject sulphur into the stratosphere, climate research has to make do with the analogy of large volcanic eruptions. Of course, assessment is still difficult here; since on the one hand there are only a few well-observed large volcanic eruptions (the last was the eruption of Mount Pinatubo in 1991) and on the other hand it is not clear how similar the reactions of the climate are to artificial and natural volcanic aerosol forcing.

Model comparison:

Since the mid-1990s, systematic model comparisons within the context of the "Coupled Model Intercomparison Project" (CMIP) have been carried out by the international climate modelling community, which also delivered essential input for the Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). To do so, identical climate scenarios are simulated using many different models (most recently by about twenty research institutes). If there is broad agreement on the simulated climate, one speaks of robust signals and assumes that these are primarily determined by the basic physics of the climate system and are only marginally dependent on specific model formulations.

With regard to CE, climate researchers have taken CMIP as an example, and since about 2010 have been simulating the possible climate effects of proposed measures for radiation manipulation in the Geoengineering Model Intercomparison Project (GeoMIP).

From Natural Science to Economic Decision-Making and Action

While climate models establish a link between emission scenarios and climate reaction, a link between regulatory intervention and changes in both emission behaviour and the related costs should be delivered using economic models. In the end, it is not just professional consideration of the uncertainties of the climate reaction alone that will be of importance for a decision in favour of or against the use of CE but rather the coupled total system, including economic components.

It should in principle also be possible to transfer the strategies described above for the detection of uncertainty to the descriptive components (see also Goeschl & Quaas, pp. 30 – 32) of economic modules – a process that until today has only been qualitatively implemented within climate economics. To this end, one would first have to work out more vigorously which components of the economic system can be looked at on which aggregation level as descriptive objects, i.e. as variables which are regarded autonomous, dynamical and unambiguously determined objects. Normative components on the other hand, insofar as they are at a level of the decision-maker, mean that the decision-maker must first be clear about his/her own basic preferences, which come before economic assessment. Here, systematizing approaches from the field of ethics can be helpful.

The UVic Earth System Climate Model

David Keller, Nadine Mengis, Fabian Reith and Andreas Oschlies

| Earth System Modelling

The University of Victoria Earth System Climate Model (UVic) used in the SPP 1689 is an Earth system model of intermediate complexity, developed at the University of Victoria in Canada. In comparison to complex Earth system models, e.g. the MPI-ESM described in the next chapter, the computation times are significantly shorter. Considerably more and longer simulations can therefore be carried out using UVic, which for example enables uncertainty analyses of model parameters and potential future scenarios.

The model consists of the following components: (1) a three-dimensional ocean model, (2) a sea ice model, (3) a terrestrial model and (4) a simple two-dimensional atmosphere model. All components have a horizontal resolution of 3.6° latitude x 1.8° longitude. The ocean component has a vertical resolution of 19 layers, which increase in thickness from 50 m near the surface to 500 m in the deep ocean.

The *ocean model* consists of a general physical circulation model and a biogeochemical ecosystem model. In the circulation model, the ocean currents and the temperature and salinity distributions are calculated on basis of physical equations. The biogeochemical ecosystem model calculates the marine cycles of carbon, nitrogen, phosphorus and oxygen.

The *sea ice model* calculates the sea ice distribution and the resulting effects on albedo[4] as well as on the transfer of heat and material between atmosphere and ocean. For this, information on surface values from the physical ocean model concerning currents and temperature is requiered.

4 | Albedo (Greek for white) describes the degree of reflectivity of the surface of the sea, the cloud surface or land surface for solar irradiation. A value of 1 means full reflection (perfect white), a value of 0 means perfect absorption of all incoming sun radiation (perfect black).

If changes in these variables occur (e.g. through climate change), the effect this would have on sea ice extent can be simulated.

The *terrestrial model* consists of a land surface model, which calculates soil properties and surface runoff, and a dynamic vegetation model that includes five vegetation classes and bare soil (e.g. deserts). It thereby calculates carbon, heat, and fresh water exchanges between ocean, atmosphere, and land surface as well as the surface albedo resulting from this.

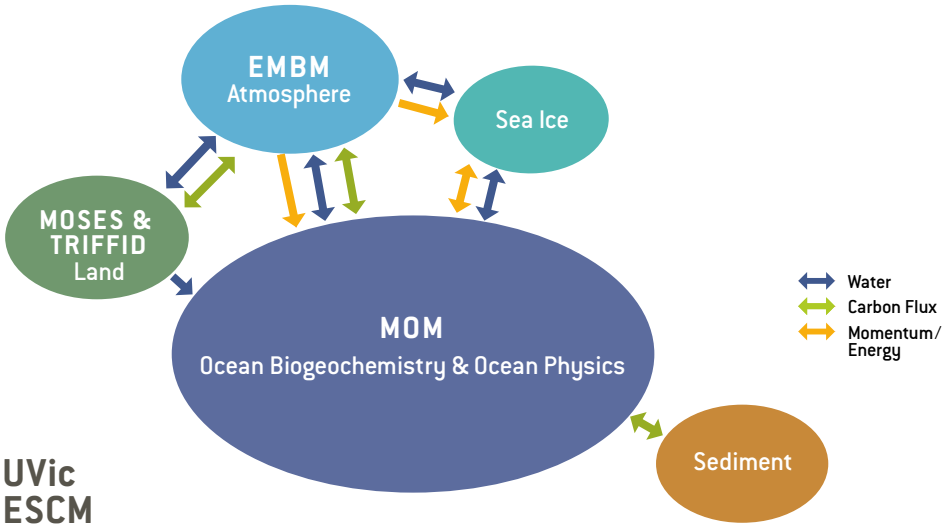
In the *two-dimensional atmospheric model*, the incoming solar irradiation that reaches the Earth's surface is calculated by considering the local albedo. Together with the long-wave radiation that is re-emitted from the Earth, the global radiation balance is determined. Based on the resulting temperature and moisture distribution and the prescribed winds, the carbon, fresh water and heat fluxes between the individual model components are determined.

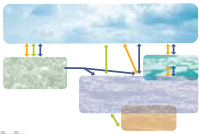
The UVic model is configured by adjusting several astronomic and geographic parameters, such as the Earth's orbital parameters, the amount of incoming solar radiation, continental ice sheet areas or the geography of major river basins for example. The concentration of CO_2 in the atmosphere can either be prescribed or varied based on different emission scenarios, for example those of the Intergovernmental Panel on Climate Change (IPCC).

The primary advantage of the UVic model when compared to more complex models is the fact that simulations are several orders of magnitude faster and can be calculated on simple computers (approx. 200 simulated years per day on a simple laptop processor). Consequently, several future CE scenarios can be simulated and each can be tested with different model parameters or emission scenarios. This allows to examine, in detail, the sensitivities of simulation results with regard to various assumptions, scenarios (e.g. different CE methods) and process

parameterizations. In this way, uncertainties in the model results can be better assessed, than would be possible with a significantly smaller number of feasible calculations possible with more complex models.

This advantage is gained by having a generally coarser resolution and a very simplified atmospheric model. Moreover, winds are not calculated by the UVic model, but rather are prescribed by external data sets. Because of this, a dynamic reaction of the atmosphere to climate changes cannot be simulated. However, changes in temperature and moisture in the atmosphere are calculated, as well as changes to the temperature and moisture transports through the prescribed wind fields. Global and large-scale changes to the Earth system simulated by the UVic model for various IPCC scenarios fall within the range of the results of more complex Earth system models.





The MPI Earth System Model

Sebastian Sonntag, Tatiana Ilyina, Julia Pongratz and Hauke Schmidt | Climate Science

The MPI-ESM (Max Planck Institute Earth System Model) is a comprehensive Earth system model that was developed at the Max Planck Institute for Meteorology. It represents the components and processes that are important for the Earth system and its changes. The model was used within the context of the model comparison study CMIP5 (Coupled Model Intercomparison Project Phase 5), which was included in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

The MPI-ESM includes processes in the atmosphere, in the ocean and on the land surface and couples these components through the exchange of energy, momentum, water and important trace gases such as carbon dioxide (CO_2). The main components of the model are (1) the atmospheric circulation model ECHAM6 and (2) the ocean circulation model MPIOM, as well as (3) the JSBACH model for the land biosphere and (4) the HAMOCC model for biogeochemistry in the ocean.
The MPI-ESM can be used with different spatial resolutions. In the SPP 1689, the model version is used with a horizontal resolution of 1.9° with 47 vertical layers in the atmosphere and 1.5° with 40 vertical layers in the ocean.

The *three-dimensional circulation model ECHAM6* calculates winds as well as the distribution of temperature, water vapour and trace gases in the atmosphere. The model is based on the equations for the dynamics of atmospheric flow and solves these on the basis of given boundary and initial conditions such as solar radiation and the chemical composition of the atmosphere. Important processes that take place on small spatial scales, such as the formation of clouds and precipitation, are parameterized in the model, i.e. based on physical considerations

and experiences from observations their effects are estimated for the individual grid points.

Analogously, the t*hree-dimensional circulation model MPIOM* calculates currents and the distribution of temperature and salinity in the ocean. Here, physical core equations for the dynamics of the currents provide the basis. In addition, a model for the sea ice distribution and its effects on matter and heat fluxes is included.

The *land biosphere model JSBACH* calculates the vegetation and its changes and from that the land surface properties as well as the exchange of water, energy and CO_2 between land and atmosphere. On the one hand vegetation is influenced by temperature, precipitation and atmospheric CO_2, and on the other hand albedo changes of the land surface or the uptake of CO_2, for example, have an influence on the atmosphere.

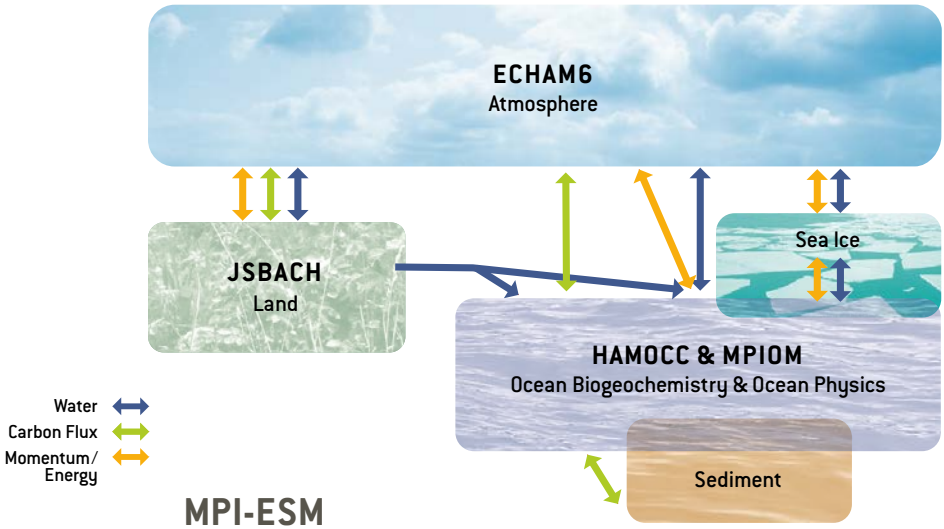
The *ocean biogeochemistry model HAMOCC* calculates the marine biogeochemical cycles of carbon, nitrogen, phosphorus, oxygen, silicate and iron in the water column and in the upper sediment layers. These depend on the ocean circulation and climate dynamics, but also influence the other components such as atmospheric CO_2 content through the exchange of CO_2 between ocean and atmosphere.

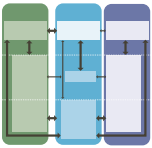
An essential feature of the MPI-ESM is the fully coupled carbon cycle, which now allows feedbacks from climate change to the carbon distribution itself to be examined. To this end, anthropogenic emissions of CO_2 from historical data or from scenarios for future development are used in the model, and the resulting carbon distribution in the atmosphere, ocean and biosphere is calculated.

Numerous processes therefore need to be calculated simultaneously at a relatively high spatial resolution in the MPI-ESM. This requires a very high computational capacity, which is only provided by super-

computers, such as that of the German Climate Computing Centre, DKRZ, in Hamburg. Nevertheless, even here only 15 years can be simulated with the model in one day.

Important characteristics of the MPI-ESM are the relatively high level of agreement between the model results and observations from the past, as well as the fact that many interacting processes are taken into consideration in the model. In comparison with Earth system models of lower complexity, this model establishes a relatively higher degree of confidence that future changes in the Earth system, as well as its reaction to human influences, can be realistically simulated.





The IPSL-CM Earth System Model

Olivier Boucher, Ulrich Platt and Christoph Kleinschmitt

| Earth System Modelling

IPSL-CM (Institut Pierre-Simon Laplace Climate Model) is a comprehensive Earth system model, developed at the Institut Pierre-Simon Laplace in Paris in collaboration with other research institutes. IPSL-CM is comprised of an atmospheric model LMDZ, a continental surface model ORCHIDEE, an ocean model NEMO and a sea ice model LIM. These components are combined together to describe the physical climate system.

The model can be extended with further components such as PISCES, a model for marine biogeochemistry, STOMATE, a vegetation model, INCA, a gas-phase and aerosol chemistry model, and REPROBUS, a model for stratospheric chemistry. The various model components interact with each other in order to best represent the complexity of the Earth system. IPSL-CM was used in the Coupled Model Intercomparison Project Phase 5 (CMIP5), which was included in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

The model is now further developed in anticipation of CMIP6. Among other things the fully coupled climate-carbon cycle in IPSL-CM is currently complemented by descriptions of the nitrogen and phosphorus cycles and their interactions with the carbon cycle. While the LMDZ model can be run in a very flexible way on a personal computer, which enables quick testing and development, the full Earth system model IPSL-CM requires very large computational power that is only available in current supercomputers.

In the SPP 1689 a version of the model with a horizontal resolution of 2.5° and 39 vertical layers in the atmosphere is used. Higher resolution versions of the model are available and can be used if and when needed. The model will be used to investigate potential limits to stratospheric

aerosol injection and marine cloud brightening, which are two of the main solar radiation management techniques that have been proposed to alleviate climate change.

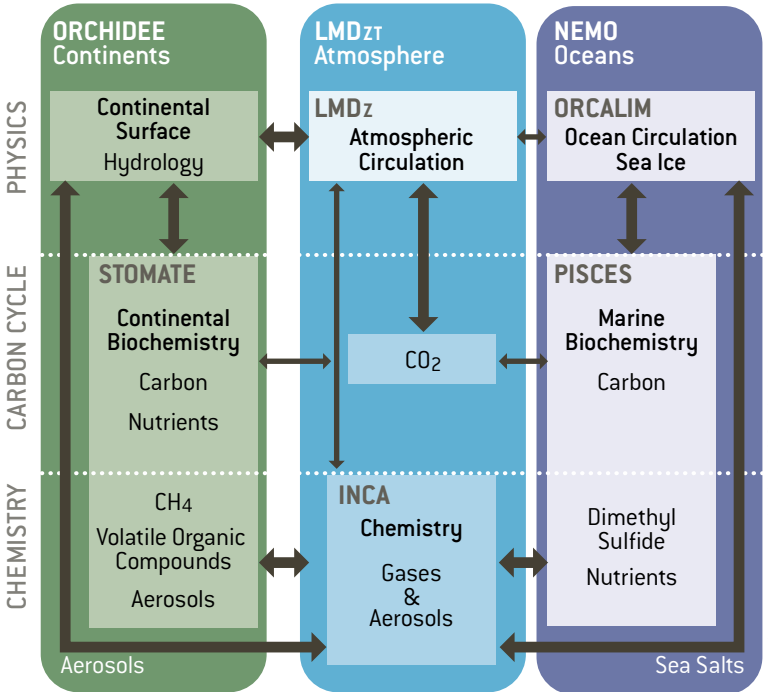
The INCA chemistry model will form the framework to investigate how stratospheric processes such as coagulation[5], sedimentation and transport of aerosols limit the potential radiative forcing achieved by stratospheric aerosol injection. In its latest version the LMDZ model includes a parameterization of atmospheric radiative transfer that has the required complexity to study the interaction of stratospheric aerosols with both solar and terrestrial radiation. Additionally LMDZ includes parameterizations of small-scale atmospheric processes — such as boundary layer mixing, convection and precipitation — which cannot be resolved by the model's equations of fluid dynamics but are required to represent the water cycle and the cloud lifecycle. LMDZ-INCA can be used in uncoupled or coupled mode with the ocean model NEMO, depending on whether the focus is on understanding the physical atmospheric processes or the climate response to solar radiation management.

Climate and Earth system models are increasingly capable of representing many of the observed features of the Earth's climate. They are extremely useful tools to investigate the climate system, climate change and to assess potential CE methods. However, they are far from perfect and are known to have many shortcomings as illustrated by systematic discrepancies in some simulated variables against regional observations.

How much confidence can be placed in the results of a model like IPSL-CM is an important and central question for the assessment of CE. A good agreement of climate model results against historical observations is required to increase our confidence. Large and well-documented volcanic eruptions such as El Chichón or Mount Pinatubo

5 | Coagulation is the process by which aerosol particles collide and stick together to form larger particles.

can be used for an evaluation of the stratospheric aerosol injection CE method and IPSL-CM itself. Other eruptions of the last millennium are less well documented but can provide a wider range of constraints. How anthropogenic aerosol pollution affects cloud characteristics is also an interesting analogue for marine cloud brightening. Comparison to observations is not the only way confidence in model results can be gained. It is also important to determine the relevant physical and chemical processes for the scientific question that is considered so as to add the right complexity to the model. Furthermore sensitivity experiments can offer valuable clues to the robustness of the results. Ultimately the model operates within a range of assumptions, which should be kept in mind to avoid over interpretation of the results.

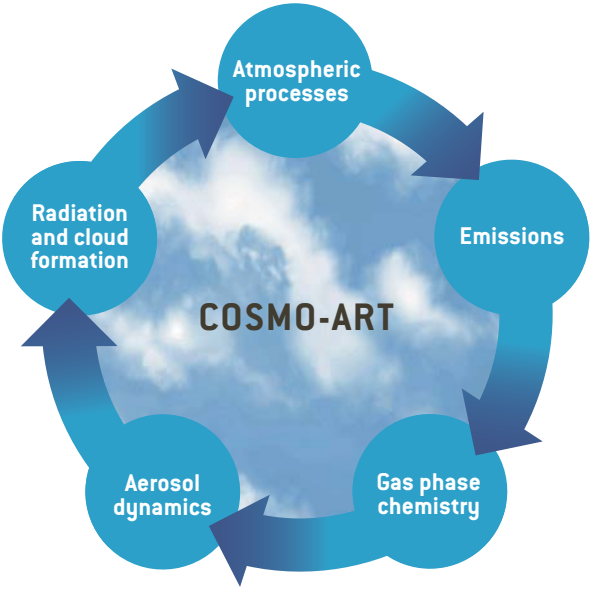


IPSL-CM

The Regional Model System COSMO-ART

Tobias Schad, Thomas Leisner and Bernhard Vogel
| Atmospheric Physics

Aerosols play an important role in the formation of clouds. Without aerosols, cloud formation would not occur, because aerosols serve as so-called cloud condensation nuclei, from which the cloud droplets are ultimately formed. Hence, the composition, and the number of aerosols play an essential role in cloud dynamics. Moreover, the optical properties, that is the radiation efficiency of a cloud, are determined primarily by the size and the number of cloud droplets. Since aerosols have an impact on the size and number of cloud droplets, this implies that they have an indirect effect on the radiation efficiency. Manipulation of these dynamics has been proposed for use in the CE method of marine cloud brightening in which additional aerosols (sea salt particles) are



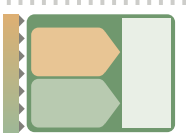
introduced into the atmospheric boundary layer to change the size and number of cloud droplets so that the cloud reflects more short-wave radiation.

For marine cloud brightening CE simulations, it is important to model the aerosol distribution as realistically as possible, as well as the interactions between aerosols and clouds. Modelling these dynamics is mostly done with two types of models. First, there are very high-resolution models, with complex descriptions of cloud microphysics, to investigate the influence of the aerosol on a particular type of cloud. Due to the computational expense of these models, the simulated area is kept as small as possible and the model can only be run for a short period of time. The second type of models are the global circulation models, which have a low spatial resolution, but can be run for a longer period of time due to the efficient parameterizations that describe some processes. However, despite being able to generally simulate the Earth's climate these models are not complex enough to simulate the interactions between clouds and aerosols.
Regional models can serve as a link between the two model types mentioned above and can thus, close the gap between the two approaches. COSMO-ART, is such a regional model and is being used to investigate the potential to brighten clouds as a method of CE.

In order to simulate the spatial and temporal distribution of reactive gases and aerosols in the atmosphere it is necessary to have both, a meteorological model and a model that can simulate atmospheric chemistry and aerosol dynamics. Therefore, the model system used here, COSMO-ART, couples the German Weather Service (DWD) weather forecast model COSMO to the Aerosols and Reactive Trace gas (ART) model. The special feature of this model system is an "on-line" coupling of gases and aerosols, which directly simulates feedback effects on the meteorology.

In addition, it offers the advantage of computing the number of cloud droplets formed from the simulated aerosols, which may be either of natural or anthropogenic origin. This explicit calculation of cloud droplets is mainly an advantage in areas where a sharp gradient in the distribution of aerosols occurs and thus, plays an important role in whitening low marine clouds, due to competition between preexisting aerosols and the aerosols added as a CE method.

Although COSMO-ART has a significantly higher resolution than global models, it still involves a degree of uncertainty. Many small-scale processes still need to be parameterized and therefore, the model represents only a simplified representation of reality. As a regional model COSMO-ART also depends on initial conditions at the boundaries (e.g. from global models), which is another source of uncertainty. An additional example of uncertainty is the emission sources themselves, since all anthropogenic emissions, which have a non-negligible influence on the efficiency of this CE method, can only be approximately estimated.



The LPJmL Vegetation Model

Tim Beringer, Lena Boysen and Vera Heck | Earth System Science

Within the Earth system, the exchange of carbon and water closely connects vegetation and soil with the atmosphere. Plants absorb carbon dioxide from the air and store carbon in new biomass, while at the same time releasing oxygen during photosynthesis. Dead plant materials are decomposed by fungi and bacteria in the soil, releasing carbon back into the atmosphere.

Today cropland and pastures cover more than 40 % of the ice free land surface. Human activities have modified the global cycles of water and carbon extensively and about 10 % of all anthropogenic CO_2 emissions are caused by deforestation and agriculture. Other ecosystems such as young, regrowing forests on the other hand act as carbon sinks and absorb about 25 % of human CO_2 emissions, thereby actively contributing to climate protection.

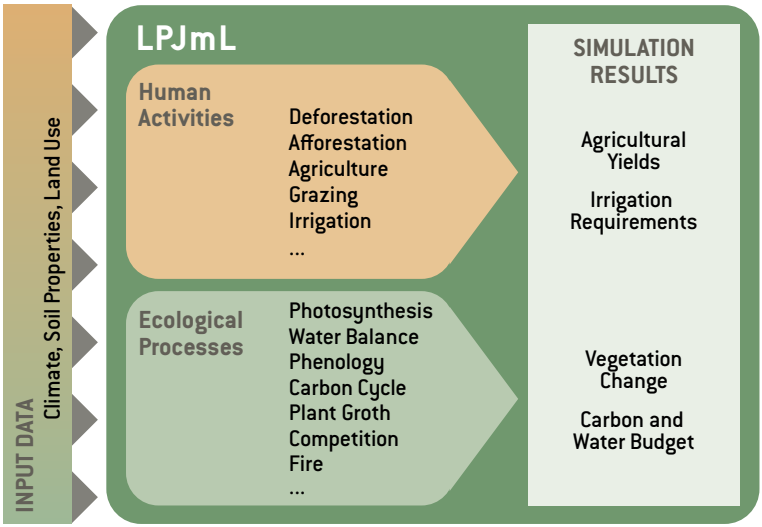
Global vegetation models have been developed to simulate and understand the manifold processes and changes in terrestrial ecosystems in the past and in the future. The LPJmL (Lund-Potsdam-Jena managed Land model) dynamic global vegetation model of the Potsdam Institute for Climate Impact Research represents both natural ecosystems and agricultural areas. LPJmL is driven by monthly fields of temperature, precipitation, cloud cover and atmospheric CO_2 concentration, as well as by information on human land use to simulate the global distribution of vegetation types, plant growth, the occurrence of fires and other ecosystem processes. The model calculates yields of the twelve most important crop types and three plant types for bioenergy production and their water demand for irrigation, as well as the productivity of grasses on pastures. It has been successfully validated against satellite observations of plant productivity, measurements of CO_2 fluxes in natural and agricultural ecosystems, river run-off, agricultural yield statistics and other observational data.

Some CE methods aim to reinforce carbon sinks, in order to reduce the atmospheric CO_2 concentration. Carbon sinks can for example be enlarged by land use strategies that aim to bind as much carbon as possible in additional plant biomass. Within the context of the SPP 1689, LPJmL is used to examine the effectiveness of large-scale afforestation projects and the cultivation of fast-growing plant types for bioenergy production. At the same time, the effects on water requirements and the competition between land for food production and environmental protection form an important part of the analyses.

Other CE methods, such as the injection of aerosols into the atmosphere to reduce the amount of incoming solar radiation, are designed to immediately reduce temperatures on the surface of the Earth. However, climate models show that these interventions can also effect the distribution and intensity of precipitation and can thereby change the growing conditions of plants. Within the context of SPP 1689, LPJmL is driven by corresponding climate scenarios in order to simulate the effects of CE on the terrestrial biosphere. This way, for example, one can examine which regions will profit from certain CE methods and where the changed climatic conditions could be disadvantageous for agricultural yields or carbon storage in vegetation and soil.

Uncertainties in the analyses result, for example, from the uncertainties in the climate scenarios used to drive LPJmL. Water availability, in particular, has a strong influence on plant growth in many regions and projections of future changes in spatial and temporal precipitation patterns differ strongly between the different climate models. Furthermore, different processes such as bacterial decomposition processes in the soil or the reaction of the plants to the increasing CO_2 content in the atmosphere are not understood exactly and their representation in the model remains therefore uncertain. Other processes are not represented in the model at all, e.g. rising occurrence of infestation of pests under increasing temperatures that may have larger impacts on plant growth in the future.

The assumptions about future CE methods represent the greatest uncertainty in the scenarios to be analysed. Whether at all, how intensively and in what form afforestation is to be implemented as a CE methods for climate protection depends on a multitude political decisions and general socio-economic conditions. Against this background, the simulations using LPJmL try to cover a comprehensive spectrum of possible future scenarios. The analyses do not represent predictions but rather should quantify potentials and possible consequences of different opportunities for actions.



Economic Modelling in the Context of Climate Engineering

Timo Goeschl and Martin Quaas | Environmental Economics

Economists employ mathematical models to describe the decision-making behaviour of economic agents in various contexts, to analyse the implications of these decisions. Agents considered may be, for example, individuals, households, firms, governments, or "the social planner", a hypothetical individual that decides on behalf of an entire society. The contexts include in particular the technological and economic constraints under which individuals choose among alternatives. Models are used to answer research questions that typically belong to one of three categories:

1. Normative questions. For example, how ought society to manage best a problem such as addressing the consequences of climate change through CE?

2. Positive (or: descriptive) questions. For example, how will economic agents respond individually or collectively to incentives that a situation such as the availability of CE presents?

3. Policy questions. For example, which policy instruments can align the choices of individual economic agents with what society believes is the best course of action?

In all three categories, economists use different analytical approaches to describe the system. These can involve static or dynamic, deterministic or stochastic optimization methods, as agents are assumed to maximize their respective objectives. For positive and policy questions, game theoretic approaches are often used to determine equilibrium outcomes in the interaction between agents.

While varying in terms of complexity, the common feature of economic models is that they are all grounded in economic theory. In the context of CE, economic models often additionally make use of insights from other

disciplines. So-called integrated assessment models (IAMs) integrate climate models and economic models (see figure 1). IAMs focus on the dynamic feedbacks between the climate system and the economy and determine possible emission and deployment paths as well as optimal mitigation of greenhouse gases over time. When normative questions are addressed, objective functions are based on ethical considerations, i.e. these models integrate insights from moral philosophy. For example, many models in (climate) economics address normative questions based on Utilitarianism.[6]

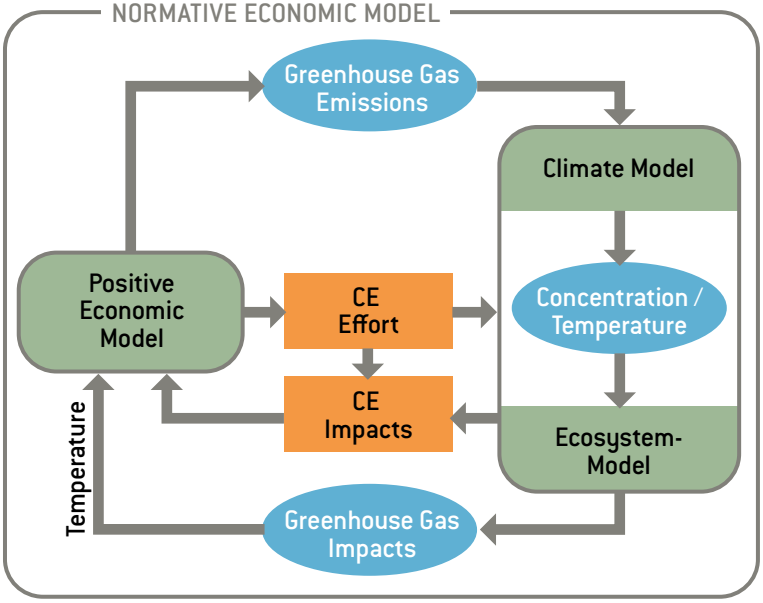


Figure 1: Integrated Assessment Models typically integrate a positive economic model of choices and a climate model to examine feedbacks and allow normative analysis as a second step.

6 | According to Utilitarian ethics, society should seek to maximize aggregate utility, i.e. the sum of individual utilities. Individual utility is assumed to be an increasing and concave function of the consumption of goods and services.

A typical example of the normative category is to decide on one or more measures of aggregate well-being of global society and to examine the existence and nature of conditions under which this measure would be raised or lowered by a certain CE method. Fully-developed IAMs that simultaneously model dynamic market equilibria and study the effects of CE have not been published so far.

Typical examples of the positive category are e.g. the use of game theory to study whether spatial heterogeneities in climate impacts give rise to strategic incentives to form coalitions of CE countries; to examine whether having significant oil reserves makes a country more likely to develop CDR capabilities; or to examine what combination of CE capabilities and mitigation efforts a current generation might choose to develop under different notions of intergenerational equity. Questions on CE belonging to the policy category have, so far, not thoroughly been addressed by means of economic modelling.

As a predictive tool, economic modelling in a CE context is until now severely constrained by data limitations, imperfections of the modelling assumptions, and unintended feedback processes. At the same time, it serves an important role: Through a systematic assessment of costs and benefits and the emphasis on incentives, economic modelling helps prevent fundamental errors of judgement in assessing CE.

CLIMATE ENGINEERING
Risks, Challenges, Opportunities?

Priority Programme 1689

In the priority programme „Climate Engineering: Risks, Challenges, Opportunities?“ (SPP 1689) we want to evaluate Climate Engineering and assess consequences of CE methods.

Sixteen universities and research institutes collaborate in nine subprojects of the Priority Programme 1689 since April 2013. The first phase of the programme will run for a total of three years, funded with nearly five million Euros by the German Research Foundation (DFG) and is coordinated by Prof. Andreas Oschlies at the GEOMAR Helmholtz Centre for Ocean Research Kiel and the KIEL EARTH INSTITUTE.

MAIN OBJECTIVES OF THE SPP 1689:

- Investigation of the climatic, ecological and social risks and potential effectiveness of different Climate Engineering methods
- Evaluation of the scientific and public perception of Climate Engineering
- Assessment – not development! – of Climate Engineering, including scientific, social, political, legal and ethical aspects

More information about the Priority Programme 1689 and the individual projects is available at: www.spp-climate-engineering.de

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“Modelling in Climate Engineering Research” on

www.spp-climate-engineering.de/modelling

CLIMATE ENGINEERING Risks, Challenges, Opportunities?

Modelling in Climate Engineering Research – Significance and Uncertainties

The term “Climate Engineering” (CE) covers various large-scale technical measures, which could be used in a targeted manner either to lower the concentration of atmospheric CO_2 or to directly influence the Earth’s radiation balance in order to counteract anthropogenic global warming.

The CE methods discussed within the research community and in the public have, until now, only been ideas for technical methods that initially appear plausible and could in principle work. However, it is difficult to examine their actual effectiveness and assess unintentional side effects, as the CE methods would be a targeted intervention in the climate system, which is a globally connected system of high complexity that is not yet sufficiently understood.

The opportunity to examine the effects and side effects of various CE methods without putting people or the environment at risk is provided by numeric models of the Earth system, which allow experiments to be carried out in a simulated world, rather than in the real natural environment.

This brochure shall help to understand the functioning, limits and possibilities of modelling to help joining the discourse on CE.

The brochure originates in the Priority Programme 1689, funded by the German Research Foundation.