Danish Meteorological Institute

Ministry for Climate and Energy

Danish Climate Centre Report 10-04

Geoengineering

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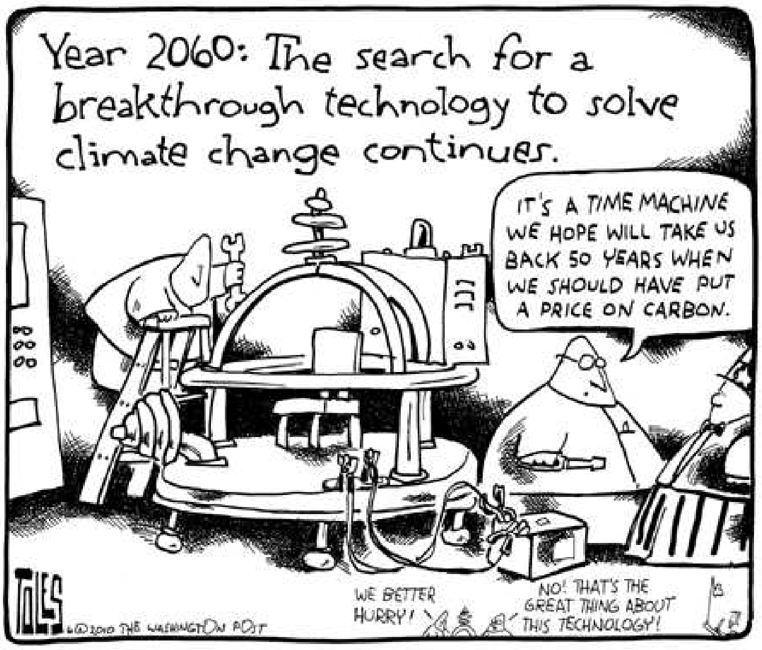

Colophone

Serial title:
Danish Climate Centre Report 10-04

Title:
Geoengineering

Subtitle:

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Responsible Institution:
Danish Meteorological Institute

Language:
English

Keywords:
Climate, climate change, geoengineering

Url:
www.dmi.dk/dmi/dkc10-04

ISSN:
1399-1973

ISBN:
978-87-7478-595-8

Version:

Website:
www.dmi.dk

Contents

1. Abstract

We describe the activities 2009-2010 in DKC regarding geoengineering. Eight relevant papers were read and discussed in the Journal Club. These papers are summarized and some general conclusions are given. The focus is on solar radiation management methods and the need for further research is emphasized. We also make suggestions for future research in geoengineering at DKC. An obvious start would be to apply EC-Earth to a subset of the experiments described in the Geoengineering Model Intercomparison Project.

2. Introduction

The interest in geoengineering at DKC was stimulated by the report from the Royal Society (Shepard et al., 2009) which we discussed on our strategy seminar in 2009. Geoengineering can be described as an intentional effort to mitigate the effects of anthropogenic greenhouse gas emissions. The report from the Royal Society described a number of geoengineering strategies and evaluated their feasibility and costs. It was emphasized in the report that geoengineering should be seen as a plan B, which should only be used if attempts to reduce the atmospheric content of greenhouse gasses fail. The main conclusion of the report is that more research is needed to investigate the possible adverse effects of geoengineering.

At the strategy seminar we decided that DKC should follow the research into geoengineering and that we should consider the possibilities of DKC to contribute to this research. It was decided that the instrument for this should mainly be the Journal Club. The Journal Club is an old and respected institution in DKC which meets every second Friday and discusses a relevant paper. The discussion is led by a volunteer who is expected to have read the paper thoroughly. We decided that the volunteer on the geoengineering papers should write a brief summary. The main part of this report is a compilation of these summaries. The different activities are discussed below.

2.1 Journal Club

The following eight papers were discussed in the Journal Club.

- Sunshade World: A fully coupled GCM evaluation of the climatic impacts of geoengineering (Lunt et al., 2008). Presented by Peter Thejll 23/10-2009
- The impact of geoengineering aerosols on stratospheric temperature and ozone (Heckendorn et al., 2009). Presented by Mette Grage 21/5-2010.
- Impact of geoengineering schemes on the global hydrological cycle (Bala et al., 2008). Presented by Bo Christiansen 4/6-2010
- Regional climate response to solar-radiation management (Ricke et al., 2010). Presented by Peter Thejll 20/8-2010.
- The Geoengineering Model Intercomparison Project (GeoMIP) (Kravitz et al., 2010). Presented by Bo Christiansen 27/8-2010.
- Efficacy of geoengineering to limit 21st century sea-level rise (Moore et al., 2010). Presented by Torben Schmith 17/9-2010.
- Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds (Latham et al., 2008). Presented by Johannes K. Nielsen 1/10-2010.
- Untangling aerosol effects on clouds and precipitation in a buffered system (Stevens and Feingold, 2009). Presented by Ulrik Korsholm 15/10-2010.

Summaries of the papers can be found in section 5.

2.2 Popular presentation at dmi.dk

DKC has in cooperation with a science journalist written a popular theme on geoengineering for DMIs web-page. It can be found here
`http://www.dmi.dk/dmi/nyt_tema_geoengineering`

2.3 Other activities

Bo Christiansen participated in a discussion meeting on "Geoengineering - taking control of our planet's climate" at the Royal Society in London, 8-9 November 2010.

3. Conclusions

Geoengineering was suggested as early as 1974 by Budyko (Budyko, 1997). More recently, the idea was suggested in an editorial by Crutzen (2006). The geoengineering approaches can be divided into two groups. The first group include methods that enhance the natural removal of CO2 from the atmosphere and includes schemes that sequester CO2 into vegetation by afforestation or genetic manipulation of plants or into the ocean by iron fertilization to increase algae bloom. The second group is often denoted solar radiation management and includes methods to reduce the incoming solar radiation. Among these methods are injection of sulphur aerosols into the stratosphere, whitening of marine clouds, and placement of reflecting mirrors into space. It is the second group of methods that we focus on in DKC as the consequences of these methods can be investigated with our current modelling tools. It is also for this group of geoengineering methods that the most serious adverse effects are expected. It is worth noting here that these methods do not attempt to solve the problem of acidification of the oceans.

Our reading in the Journal Club and our other activities have led to the following main conclusions. For a more comprehensive review see e.g. Robock (2008).

- More research is needed, in particular studies with state-of-the-art climate models. Many questions are still unanswered especially regarding seasonal and regional aspects where existing model studies often give different results.
- The radiative effect of a doubling of CO2 can be balanced by an 1.8 % reduction of the solar constant. Even though the two forcings have different regional and seasonal patterns the global annual mean temperature can be surprisingly well mitigated.
- Global annual mean temperature and precipitation can not be mitigated at the same time. The short-wave solar forcing has a more direct impact on the surface and thereby a larger influence on the hydrological cycle than the long-wave forcing from green-house gases.
- Temperature and precipitation are probably not very well mitigated on regional and seasonal scales. Climate model experiments often give different results.
- The presence of aerosol particles in the stratosphere will enhance the destruction of the ozone layer.
- The effect of stratospheric aerosols might be slower than linear. This means that an accelerating amount of aerosols will have to be deployed to obtain the wanted radiative effect.
- Crude calculations show that whitening of marine stratocumulus might be a possibility. An emission of 23 m^3 droplets of sea water per second near the surface could maintain a negative

forcing of 3.7 W/m^2 (corresponding to a doubling of CO2) . This could be done by a fleet of a few thousand ships. However, the micro-physics of clouds is not well understood and the assumptions of the calculations may very well be broken, in particular the assumption that only the first indirect effect is important.

- By applying moderate solar management methods the global sea level rise can be constrained to about 50 cm in 2100 compared to the about 80 cm without.

- The solar radiation management methods do not stop the acidification of the oceans which is a consequence of the oceanic uptake of the increased levels of CO2. It is estimated that the oceans are already 30 % more acid than in pre-industrial/industrial times. The acidification has severe consequences for life in the oceans.

4. The future of geoengineering in DKC

The solar radiation management methods can in their simplest forms easily be studied in climate models. Many of the published studies (and those suggested in GeoMIP) apply a simple reduction of the solar constant. Such model experiments can give insight into the mitigation of the influence of green-house gases on the different parts of the climate system such as surface temperature, precipitation, sea ice etc. An interesting issue could be the situation in the NH extra-tropical winter. Here the effect reduced incoming solar radiation is not direct but may come from changes in the dynamics including the stratosphere. This situation has been studied in the context of explosive volcanic eruptions. In the first years after these eruptions an enhanced positive phase of the NAO is found connected to a stronger stratospheric vortex.

The EC-Earth climate model at DKC is ideal for these kind of experiments because it has a very good representation of the stratosphere. The stratosphere has been improved and will be tested in the ongoing EU-fonded project COMBINE. EC-Earth does not at present include a full tested aerosol scheme.

We suggest that DKC early in 2011 starts performing solar radiation management experiments as described in GeoMIP [1] (see also 5.5 below).

G1 An equilibrium experiment involving an quadrupling of CO2. The increase of CO2 will be instantaneous and the effect will be balanced by a instantaneously change of the solar constant. A quadrupled CO2 experiment is needed so that the necessary radiative forcing can be calculated.

G2 A transient experiment with a 1 % per year increase in CO2. The global radiative forcing from CO2 will be balanced by gradually reducing the solar constant. An experiment with only increasing CO2 will be needed to deduce the necessary reduction in the solar constant.

Both these experiments fit within the frame of CMIP5. Each experiment will last for 70 years and an ensemble of experiments would be preferable. The results should be submitted to an international database. It is also important that DKC itself analyze the results. Here focus could be on the NH extra-topical winter, the stratosphere, or sea/ice.

[1] For more on GeoMIP see `http://climate.envsci.rutgers.edu/GeoMIP/index.html`

DKC already have relevant experience in global modelling including radiative forcing and the stratosphere. Kindem and Christiansen (2001) investigated the impact of stratospheric ozone depletion on the NH extra-tropical winter circulation and Christiansen (1999) looked at the differences in surface temperature and energy balance between long- and short waves forcings from ozone changes.

5. Summaries

This chapter contains the summaries of the eight papers read in the Journal Club.

5.1 Sunshade World: A fully coupled GCM evaluation of the climatic impacts of geoengineering

The article discusses one of the conceptually simplest ides for a geoengineering solution to the global warming - the installation of reflective mirrors between the Earth and the Sun to reduce incoming solar radiation. The idea was originally put forward by mirror-specialist Roger Angel who suggested putting many small mirrors into space in a diffuse distribution.

The authors investigate the impacts of this idea for the first time within a fully coupled General Circulation Model. To offset the effect of 4xCO2 the authors impose a 57 W/m^2 reduction in the SW insolation. This is applied evenly at all latitudes - as if a filter had been inserted over the Sun casting all of the Earth into a slightly reduced beam of sunshine.

They found significant cooling of the tropics, warming of high latitudes and related sea ice reduction, a reduction in intensity of the hydrological cycle, reduced ENSO variability, and an increase in Atlantic overturning.

The paper points out that while not all impacts of unmitigated greenhouse effects are removed by the geoengineering idea the remnant impacts are small compared to the unmitigated situation - except for the acidification of the oceans.

The discussion at the Journal Club noted that no regionally differentiated insolation change was explored in the paper, but that this would not - at least conceptually - be hard to achieve from space.

5.2 The impact of geoengineering aerosols on stratospheric temperature and ozone

In this article the authors address how injecting SO2 into the lower tropical stratosphere will affect the micro-physics and the chemistry of the stratosphere and tropopause. They use a 3D chemistry climate model, fed by aerosol size distributions from the AER zonal mean 2D aerosol model. Scenarios with 1-10 Mt/Y SO2 injections are investigated.

Scenarios with continuous injection of SO2 predict that with perpetually freshly formed particles, the particles are predicted to grow to larger size by efficient coagulation. In their calculations aerosol particles grow sufficiently large for allow for gravitational settling, furthermore the large particles have a smaller albedo than the smaller ones. The predicted global net SW flux at the earth's surface is therefore much smaller than predicted in other (earlier) studies where the micro-physics of the aerosols have not been taken into account. By pulsing the injections at a rate of two pulses per year, a 5 Mt/Y pulsed injection becomes as efficient as a 10 Mt/Y continuous injection, but still not as efficient as assumed earlier.

Effects of the stratosphere assessed: Enhanced ozone depletion as a consequence of a lowering of the NOx/NOy ratio leading to an increase in the ClOx/Cly ratio. Enhanced HOx catalyzed ozone destruction, as a consequence of increased heating of the tropical tropopause leading to more H2O in the lower stratosphere.

Further warming effect assessed (first time assessed): Warming as a consequence of more water vapor coming from the heating of the tropical tropopause.

5.3 Impact of geoengineering schemes on the global hydrological cycle

While previous equilibrium model studies have shown that if incoming solar forcing is decreased by an appropriate value then the temperature increase due to a doubling or quadrupling of CO2 could be mitigated. This could happen even in seasonal and regional means. This is somewhat surprising as the radiative forcing of CO2 and incoming solar radiation have different temporal and spatial patterns. The present paper investigates if a similar compensation will take place for precipitation. A decrease in precipitation has been seen after Pinatubo which is often taken as a analog to solar radiation management schemes.

The paper analyzes existing equilibrium simulations with CCM3 coupled to a slab ocean. The simulations include a control experiment, a "2xCO2" experiment, a "solar" experiment with incoming solar radiation decreased with 1.8 %, and a "stabilized" experiment with both 2xCO2 and reduced solar radiation.

In global annual mean the temperature increases with 2.4 K in the "2xCO2" experiment and decreases with approximately the same amount in the "solar" experiment. In the "stabilized" experiment has global annual mean temperatures very similar to the control experiment. Also when looking at geographical changes the "stabilized" experiment show much smaller temperature changes than the 2xCO2 experiment. Water vapor content in the atmosphere also shows a clear mitigation in the "stabilized" experiment. However, the situation for precipitation is different; precipitation increases with 3.7 % in the "2xCO2" experiment but decreases with 5.8 % in the "solar" experiment. Likewise, precipitation in the "stabilized" experiment is 1.7 % less than in the control experiment.

To explain this lacking mitigation of precipitation the paper presents a study of the energy balance at the surface. The explanation turns out to be similar to the mechanism described in Christiansen (1999). Changes in solar radiation is felt at the surface to a larger degree that changes in the long-wave forcing from CO2. Changes in the solar radiation will therefore more easily change the hydrological cycle.

As many other paper about geoengineering the authors carefully presents arguments against using this option. Here it is mentioned that solar radiation methods do not deal with the harmful effects of ocean acidification. The ozone layer may be harmed and commitments may have to be maintained over many centuries.

5.4 Regional climate response to solar-radiation management

What they did: Ran many AOGCM simulations of changes in a) globally-smooth volcanic-type short-wavelength forcing and b) realistic anthropogenic forcings. Used ocean-simplified AOGCM. Considered those runs that managed to stabilize global-mean SATs to within 1/2 degree of simulation start value. Found that global-mean precipitation goes down, but that regional changes in precipitation and temperature are not similar in different regions. Comment that it will be difficult to find SRM scenarios that make all regions equally happy, particularly in the long run.

Major comment from Journal Club group: That Figure 3 should be interpreted carefully: It is not obvious what it shows - is it the mean responses in India and China - or is it one realization of the evolution for China and another for India, labelled by the corresponding global mean SATs? Even if it is the mean responses then the nature of the variability of the numbers averaged should be known before the mean can be easily interpreted. Supplementary material Figures S4-S6 may hold some of the answer, but are hard to interpret visually.

5.5 The Geoengineering Model Intercomparison Project (GeoMIP)

The paper proposes a series of standard forcing scenarios for climate models with the purpose of evaluate the efficacy and risks of geoengineering with stratospheric aerosols.

It has been argued that the most feasible geoengineering approach is through stratospheric sulfate aerosols. Such a scheme would also be relatively cheap. However, it has been pointed out that stratospheric geoengineering would have potential harmful consequences on e.g. the ozone layer and the hydrological cycle. Several groups have performed experiments but these cannot be directly compared due to different implementations of the effect of the stratospheric aerosol. Different models give different results in particular regarding the regional effects.

To solve such problems the authors suggest a suite of standardized climate modelling experiments which individual groups can easily perform. The results should be submitted to an international database so that they can be openly studied. The tree experiments are called G1, G2, and G3. The models involved should at least include the atmosphere and the ocean.

G1 is initiated from a control run. CO2 will be instantaneously quadrupled and the effect will be balanced by a instantaneously change of the solar constant. A quadrupled CO2 experiment is included in CMIP5 and from this experiment the necessary radiative forcing can be calculated.

G2 will be a transient experiment but still involve a reduction of the solar constant. It is build on a CMIP5 experiment specifying a 1 % per year increase in CO2. In G2 the global radiative forcing from CO2 will be balanced by gradually reducing the solar constant.

G3 will be more realistic as it involves the aerosols. It uses the RCP4.5 scenario starting in 2020. Stratospheric aerosols will be added gradually to balance the anthropogenic forcing. G3 will involve some kind of aerosol modelling.

In the experiments the geoengineering phase will last 50 years and the models will be run additionally 20 years to study the response to stoppage of geoengineering. It is expected that an ensemble of experiments with different initial conditions is performed.

5.6 Efficacy of geoengineering to limit 21st century sea-level rise

By applying a previously developed statistical model relating changes in radiative forcing to sea level changes, this paper investigates the prospect for reducing sea level rise by geoengineering . They investigate geoengineering options to limit incoming solar radiation and to alter the carbon cycle. Here it worthwhile mentioning that only the latter class of methods do anything to avert acidification of oceans (known as ’the second CO2 problem’) due to rising CO2-concentrations in the atmosphere.

The effect of an annual SO2-release equivalent to one Mt. Pinatubo every 4 years and of placing 20 million tonnes of mirrors in space (both are comparable to reduction of the radiative forcing by year 2100 of 4 W/m2, which corresponds to a doubling of the CO2 concentration) show that sea level will continue to rise at slightly reduced rates and sea levels would be 30-40 cm lower by year 2100 with these two geoengineering scenarios relative to the three RCP scenarios considered.

The authors also investigate three different methods to biologically remove CO2 from the atmosphere, namely: afforestation/reforestation, biochar production and Bioenergy with carbon storage (BECS). Of these, BECS turns out to be the more efficacious, with the potential to reduce sea level by about 20 cm by year 2100 relative to the three RPC-scenarios considered. Again, we remind, that these methods in addition also contribute to solve 'the second CO2-problem' of oceanic acidification.

The main conclusion of the paper is that the moderate geoengineering options can constrain global sea-level to about 50 cm above 2000 levels in the RCP3PD and RCP4.5 forcing scenarios, but for the RCP8.5 scenario, aggressive geoengineering is needed for a similar constrain.

5.7 Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds

The paper provides the rationale behind albedo enhancement by seeding of marine stratocumulus. First Latham et al. estimates, from rather crude assumptions, the aerosol production rate needed to maintain a negative global radiative forcing of 3.7 W/m^2. It turns out that globally we would need to produce 23 m^3 micron sized droplets composed of sea water per second - and just emit them near the sea surface - in order to achieve that goal. In the calculation it is assumed that half of the emitted particles escapes the boundary layer and enters a stratocumulus deck, which seems as a rather arbitrary assumption. The cloud albedo change is calculated from a simplistic parameterization as a function of droplet number density.

In a companion paper by Salter et al. it is demonstrated that production rates of this order of magnitude is feasible. Basically the idea here is to build a fleet of some few thousand ships driven by solar and wind energy to constantly traverse the oceans while spraying ocean water into the boundary layer.

In the second half of the paper, Latham et al. test their idea in two different global models (HadGAM and NCAR-CAM). The model runs are performed by controlling the cloud droplet concentration, and observe how it affect the drop size, liquid water path, albedo and short wave cloud albedo forcing. The model runs do not agree too well, but they are used to locate areas where the effect of these operations would be largest. Even with the rather primitive two moment micro-physical schemes of these models it turns out that in some areas the albedo effect is reversed, i.e. the clouds seeding increases the radiative forcing.

It is concluded that the scheme could work if some outstanding issues are solved. These issues include the actual cloud scale dynamics, possibly unforeseen global scale dynamical changes and a few not too severe engineering problems. It is also pointed out that the effect is nonlinear, so the scheme could balance a CO2 doubling, but certainly not a factor 10 increase of CO2. On the pro-side it is noted that the scheme is reversible. If it turns out that there is some unforeseen environmental effect the program may be cancelled and the atmosphere would return to normal within a few days.

5.8 Untangling aerosol effects on clouds and precipitation in a buffered system

Basic point of the article: detailed modeling shows that the originally suggested sensitivity of precipitation release to changes in aerosol burden may be too strong.

There are buffers in the system that acts to decrease the sensitivity. These are in the form of processes that tend to restore the system towards its starting point e.g. (micro-physics-dynamics buffer) increased aerosol burden leads to suppression of light drizzle in stratocumulus which in turn leads to decoupling from the surface and smaller cloud fraction (as opposed to the original suggestion that cloud fraction should increase) . The article gives several examples of such buffers rooted in results from cloud resolving model simulations. Since, observations are currently not sufficient and it is inherently difficult to observe the 2. indirect effect we do not know which buffers are of greatest importance. Aerosol indirect effects are therefore associated with a large degree of uncertainty.

Relation to Latham's geo-engineering idea: the calculations performed by Latham implicitly assumes that the 1. indirect effect acts alone and that cloud liquid water remains constant as aerosol burden increase. Since, this is an unlikely scenario and since the effects of letting cloud water vary are more or less unknown (this is a connection to the discussed article) the calculations does not seem certain, at least arguments for neglecting the effects should be presented. Note that ship tracks are a somewhat special case in the sense that they require shallow, relatively stable, boundary layers without too much dispersion. The numbers of injected aerosols is very large and confined in the horizontal. Also the size distribution and composition are of importance.

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