Tim Lenton
Naomi Vaughan *Editors*

Geoengineering Responses to Climate Change

Selected Entries from the Encyclopedia of Sustainability Science and Technology

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Chapter 1
Introduction

Timothy M. Lenton and Naomi E. Vaughan

This section focuses on ideas to deliberately remedy anthropogenic climate change, either by actively removing greenhouse gases from the atmosphere or by decreasing the amount of sunlight absorbed at the Earth's surface. The technologies discussed are commonly grouped under the term "geoengineering," defined in a 2009 report by the Royal Society as the "deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change." Geoengineering methods can be contrasted with more conventional approaches to mitigating climate change that involve reducing the emissions of greenhouse gases, especially carbon dioxide (CO_2). However, there is some overlap as enhancing the sinks of greenhouse gases, for example, by afforestation, can be described as both geoengineering and mitigation. (The Intergovernmental Panel on Climate Change (Working Group III) states that "mitigation means implementing policies to reduce greenhouse gas emissions *and enhance sinks*" [our emphasis].)

Failure by the international community to make substantive progress in reducing CO_2 emissions, coupled with recent evidence of accelerating climate change, have brought urgency to the search for additional means of tackling climate change. This has fueled much recent debate about geoengineering and a flurry of mostly model-based research studies. There is widely expressed concern that undertaking, or even discussing, geoengineering poses the "moral hazard" of reducing efforts to tackle the root cause of climate change, namely, greenhouse gas emissions. However, few

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of those researching geoengineering advocate it as an alternative to reducing greenhouse gas emissions. Instead, current discussions are usually framed in terms of the possible use of geoengineering *in addition to* reducing greenhouse gas emissions in order to limit the magnitude of climate change, for example, to stay within the widely discussed policy "threshold" of limiting global warming to 2°C above preindustrial.

The technologies discussed herein can be subdivided into those involving carbon dioxide removal (CDR) from the atmosphere, and those involving reflecting sunlight, referred to by the Royal Society as "solar radiation management" (SRM) (although the word "management" implies a high level of understanding of the system in question that is probably not justified for the climate). The distinction can also be thought about in terms of wavelengths of radiation; short-wave geoengineering tries to reduce incoming sunlight, while long-wave geoengineering tries to reduce the return flux of heat to the surface from the increased blanket of heat-absorbing gases in the atmosphere. Sunlight reflection can never perfectly counterbalance an increased greenhouse effect because the two types of downwelling radiation have different spatial and seasonal patterns.

The section presents some of the more widely discussed geoengineering options, without being comprehensive. Here, we try to fill some of the gaps as well as introduce the entries herein.

Sunlight Reflection (SR)

Sunlight reflection can act rapidly to cool the climate if deployed on a sufficiently large scale. It could, in principle, be deployed to return the Earth to its preindustrial temperature, to hold it at some level of warming that has already occurred, or to lower future global warming. A popular framing is that sunlight reflection could "buy time" for decarbonising the economy and allowing greenhouse gas concentrations to stabilize and then come down. Alternatively, potent methods of sunlight reflection might be reserved for use "in emergency" should dangerous climate change become apparent, but it is as yet unproven that such a deployment after a threshold had been passed would prevent the change that was already underway.

Methods of sunlight reflection can be distinguished in terms of the altitude at which they are applied. They start outside the Earth's atmosphere with the idea of placing mirrors or sunshades in space to reduce the amount of sunlight reaching the Earth (D. J. Lunt "Sunshades for Solar Radiation Management"). To counteract a doubling of atmospheric carbon dioxide would require a roughly 2% reduction in the amount of sunlight reaching the top of the Earth's atmosphere. To achieve this, one proposal is to put tiny "flyers" (each about 0.3 m^2) between the Earth and the Sun at the first Lagrangian (L1) point. The roughly 5 million km^2 of sunshade required at this distance (around 1.5 million km) means the method will probably remain in the realm of science fiction for the foreseeable future. However, the model studies that have been conducted to examine the effects on the climate provide useful information on the effects of a uniform reduction in incoming sunlight, which might be achieved by other means.

Currently, the leading candidate for geoengineering a reduction in incoming sunlight is to inject tiny particles into the Earth's stratosphere which will scatter (or in some cases absorb) sunlight (B. Kravitz "Stratospheric Aerosols for Solar Radiation Management"). (The stratosphere is the thermally stratified layer of the Earth's atmosphere between about 10 and 50 km altitude, separated from the well-mixed troposphere below by the tropopause.)

A natural analogue here is a volcanic eruption, such as Mt. Pinatubo in 1991, which injected sulfate aerosol into the stratosphere and measurably cooled the climate (by around 0.5°C in the following year, followed by a tailing off). The stable thermal structure of the stratosphere means that aerosols stay aloft for much longer than in the troposphere below, and therefore, a much smaller loading of particles is required to have a given cooling effect. An estimated 1.5–5 MtS year^{-1} would need to be deliberately injected into the stratosphere to offset a doubling of CO_2, which is much less than the 50–100 MtS year^{-1} that human activity currently adds as pollution to the troposphere. The main unanswered questions surround how to inject sulfate aerosols into the stratosphere in a way that stops them from coagulating, because if the tiny particles combine to become larger particles, this can profoundly alter their radiative properties, at the extreme, turning a cooling effect into a warming effect. Other types of aerosol, notably soot, and engineered metal nanoparticles are also being discussed as possible candidates for stratospheric injection.

Moving down into the lower atmosphere, clouds are a major contributor to the reflectivity of the planet, and low-level clouds in particular have a net cooling effect at the surface. Hence, it has been proposed to cool the planet by making marine stratocumulus clouds more reflective (S. H. Salter "Solar Radiation Management, Cloud Albedo Enhancement"). This can be achieved by distributing the same amount of cloud water over more but smaller droplets, which requires a source of the tiny particles known as cloud condensation nuclei on which water condenses. Sea salt is the most obvious and ubiquitous candidate aerosol, and a means of spraying it from the ocean using wind-powered boats with Flettner rotors is described by Salter. An alternative is to enhance the source of cloud condensation nuclei from the biological production and air-sea exchange of the gas dimethyl sulfide. The methods may also suppress rainfall, increasing the lifetime of clouds and giving a further cooling effect. They should be most effective far from sources of human pollution (which also provide condensation nuclei), such as in the Southern Ocean. However, this means the cooling effects on the climate would inevitably be patchy, which in turn can cause unexpected climate changes far away, for example, in some model simulations, the Amazon gets drier.

Finally, a number of proposals have been made to enhance the reflectivity of the Earth's surface, focusing on deserts, grasslands, croplands, and human settlements. Here, the total area altered and the change in surface reflectivity (albedo) are the key determinants of the global cooling effect. As the land comprises only 29% of the Earth's surface, to achieve a significant global cooling effect would require major overcooling of parts of the land. Instead, these approaches are best thought of as means of achieving significant localized cooling. In the case of more reflective croplands, cooling effects would be largest just before the crop is harvested, so this could provide a means of, for example, cooling future European summers. However, there remain unanswered questions regarding the effects on crop yield. Reflective roof surfaces are now legislation in California and more widespread adoption of this approach could become an important adaptation strategy in tackling urban heat islands, even though its global cooling effect will be negligible.

Carbon Dioxide Removal

Current total CO_2 emissions from fossil fuel burning, land-use change, and cement production are rapidly approaching 10 billion tons of carbon per year ($\sim$10 PgC year^{-1}). Just to stop CO_2 concentration from rising in the atmosphere, the net anthropogenic source of CO_2 has to be reduced first by about 50% to match natural sinks and, then on, down to zero as the natural sinks decay. To help achieve this, carbon dioxide removal (CDR), and subsequent storage, is a clear complement to reducing CO_2 emissions. Doing both together could stabilize atmospheric CO_2 concentration sooner and at a lower level. Ultimately, CDR could be used to bring the concentration of atmospheric CO_2 down faster than natural sinks, to whatever is deemed a safe level. However, like reducing emissions, CDR will act relatively slowly to alter the rate and magnitude of climate change when compared to potent methods of sunlight reflection. To achieve significant global CO_2 removal, even with the most effective CDR methods, will require global deployment for decades. Furthermore, the Earth system actually works against deliberate CDR by always trying to maintain a balanced apportioning of CO_2 between the ocean, atmosphere, and land surfaces. Hence, if CO_2 is removed from the atmosphere, some leaks out from the ocean and/or land to partly compensate, meaning that the effect on atmospheric CO_2 concentration decays over time. (This is simply the opposite of the well-known land and ocean carbon sinks, which are generated by the addition of CO_2 to the atmosphere.)

Carbon dioxide removal covers a wide range of methods and pathways to storage. CO_2 can be removed from the air by photosynthesis (by plants, algae, or cyanobacteria) or by physical and chemical means, which are related to natural weathering reactions. The ease of removal varies with the pathway. The carbon may ultimately be stored as liquid CO_2 (in geological reservoirs or the deep ocean), in charge-balanced solution in seawater, as carbonate rocks, as charcoal, or as buried or standing biomass. The different forms of storage have differing stability in terms of thermodynamics, kinetics of reactions, and ease with which CO_2 might be returned to the atmosphere.

Photosynthesis is effectively solar-powered carbon capture for free (to us), although it is remarkably inefficient ($\sim$0.5% efficiency, compared to solar photovoltaic cells capable of ~20% efficiency), and biomass is the least stable form of carbon storage because it is a source of energy to other organisms. However, in the ocean, some of the carbon fixed in photosynthesis can sink to depths where it has a lifetime of up to 1,000 years. The amount exported to depth depends crucially on the supply of limiting nutrients to the surface ocean. Hence, several geoengineering proposals consider adding limiting nutrients, especially iron, to the surface ocean to stimulate biological productivity (P. W. Boyd "Ocean Fertilization for Sequestration of Carbon Dioxide from the Atmosphere"). Iron fertilization is unusual in being a form of geoengineering that can draw on a series of 12 experiments to investigate its biogeochemical consequences (though not geoengineering specifically). However, what those experiments have shown is that it is remarkably difficult to increase the sinking flux of carbon to the deep ocean. Model studies add that even with global iron fertilization maintained for a century, the potential impact on atmospheric CO_2 concentration is modest, lowering it by, at most, around 30 parts per million.

Land-based photosynthesis has the potential to fuel larger carbon dioxide removal fluxes, despite the smaller surface area of the land compared to the ocean and the need not to take land from natural ecosystems or to interfere with food production. The potential is greater because of the high productivity that can be achieved on land. The simplest method is afforestation, but it only works as a means of carbon dioxide removal if the conversion to forest is permanent and the carbon that is lost as trees decay is replaced by new trees. Still, afforestation is already underway at a global scale, with around 250 million hectares having been planted in recent decades, and this is creating a sink of circa 0.3 PgC year^{-1}, canceling roughly 3% of current total CO_2 emissions.

Carbon dioxide removal can also be achieved by converting waste biomass from farming and forestry into longer-lived forms for storage, although the long-term potential will depend more on the supply of deliberately cultivated biomass energy crops. Several conversion pathways are available. Biomass energy combustion coupled with capture and storage of the CO_2 given off (often referred to as BECS or BECCS) is more cost-effective than chemical methods of CO_2 air capture, although there are still energy penalties in capturing and compressing CO_2. Fermentation of biomass, for example, to produce liquid biofuels, yields a near-pure stream of CO_2 reducing the capture cost. Alternatively, pyrolysis of biomass (in the presence of little or no oxygen) produces charcoal, which can be returned to the soil as biochar (S. Shackley et al. "Biochar, tool for climate change mitigation and soil management"). Although the energy yield from pyrolysis is somewhat less than from combustion, biochar has a range of cobenefits, including improving soil water retention and fertility, which make it an attractive option. Energy remains in the biochar, but it is hard for organisms to break the material down, making much of it long-lived in soil.

Carbon dioxide can also be captured from the air by chemical means, using, for example, a strong alkali solution. When CO_2 has been captured into concentrated form in this way, or from combusting or fermenting biomass, it can be stored in liquid form. However, it is safer and more permanent to neutralize carbonic acid to form carbonate rocks or aqueous bicarbonates by mirroring natural rock weathering processes. Carbonate weathering brings CO_2 into solution as bicarbonate (although, ultimately, on a ~10,000-year timescale when carbonates are redeposited in the ocean, the CO_2 will be returned to the atmosphere). Silicate weathering followed by carbonate deposition is a permanent removal process for atmospheric CO_2. However, these reactions are generally rather slow, even when applied to a CO_2-rich gas stream. Heating to speed up the reactions is too costly; hence, better methods for accelerating carbonation are needed, and some work on using electrochemical energy to accelerate the reactions is underway.

Finally, CO_2 can be removed from the air by mining, crushing, and spreading on the land silicate minerals that weather rapidly such as serpentine or olivine (R. D. Schuiling "Carbon Dioxide Sequestration, Weathering Approaches to"). This represents a direct attempt to accelerate silicate weathering, which should be most effective in wet regions of the tropics under vegetation, because plants and their associated mycorrhizal fungi produce organic acids that accelerate dissolution. Olivine has relatively large deposits in the tropics, making it a promising candidate, although estimates are needed of the energy and CO_2 costs of mining, grinding, and distributing the rock on appropriate land. Weathering rates can be limited by factors other than substrate supply, and current estimates suggest this CDR method may be limited to at most around 1 PgC year^{-1}.

Broader Issues

The concept of geoengineering and the particular proposals, both CDR and SRM, provoke a plethora of social concerns ranging from specific questions of economical or political feasibility for each proposed method to broader ethical and philosophical debates about our relationship with nature.

Efforts are underway to establish a framework for governing geoengineering, particularly SRM. This poses a host of questions, relating both to research and possible implementation (S. Low et al. "Geoengineering Policy and Governance Issues"). Historical efforts at weather modification provide some past precedent (albeit at a smaller scale), but they offer little in the way of existing governance frameworks to draw on. Given the rapidly evolving nature of the field, flexibility and adaptability will be key requirements for whatever governance framework emerges.

The use of any geoengineering method as a response to climate change will ultimately be made by societies. Therefore, the public perception of, and engagement with, this group of emerging technologies is of critical importance in determining their future usefulness. Concepts of upstream engagement and responsible innovation can help incorporate a range of societal values into research at an early stage (and they are both, in different ways, built into two current UK Research Council–funded projects on geoengineering).

Early public engagement (e.g., "Experiment Earth" conducted by the UK Natural Environment Research Council) has already yielded unexpected responses to geoengineering. In particular, the "moral hazard" argument that geoengineering will suppress efforts to reduce greenhouse gas emissions has not been clearly borne out. Some members of the public responded to information on geoengineering with the opposite response; that if things are so bad that scientists are considering geoengineering, then efforts to reduce the root cause of climate change, namely, greenhouse gas emissions, must be strengthened.

Moving forward, the ethical and philosophical debate about geoengineering needs to distinguish SRM and CDR techniques. SRM only deals with the symptoms of climate change, notably rising temperatures. CDR, on the other hand, like conventional emissions reduction, tackles the root cause of climate change: rising greenhouse gas concentrations. Specific methods still raise specific concerns. But as research on geoengineering continues to escalate, we hope this section provides a stimulating introduction to the methods and the debates surrounding them.

Chapter 2
Sunshades for Solar Radiation Management

Daniel J. Lunt

Glossary

Geoengineering	The intentional large-scale manipulation of the environment.
Solar radiation management	Deliberate modification of the solar radiation budget, by either changing the amount of sunlight entering the Earth's atmosphere, or by changing the Earth's reflectivity, normally in an effort to counteract human-induced climate change.
Sunshade	A colloquial term for a giant reflector, or array of smaller reflectors, in orbit between the Earth and the Sun. Also known as a "space mirror."

Definition of the Subject and Its Importance

There is strong scientific consensus that the Earth's climate has been warming over the last century and that this warming is primarily due to human influences on the climate system (IPCC 2007). Attempts to curb human emissions of greenhouse gases have so far largely failed; as such, and in an attempt to avoid or delay potential dangerous climate change, several geoengineering schemes have been suggested for modifying Earth's climate directly. One such scheme is the construction of a sunshade in space, in

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orbit between the Earth and the Sun, with the aim of reducing the effective strength of the Sun's rays, and cooling the Earth's climate. However, it is now thought that such a sunshade, although highly effective in terms of cooling the planet, would have other, perhaps undesirable, impacts on Earth's climate, in particular on precipitation patterns. This highlights the importance of using a whole-Earth system approach when considering the potential impacts of any geoengineering scheme.

Introduction

One of the first references to a space-based sunshade was proposed in the context of modifying the climates of extraterrestrial planets, with the aim of making them habitable [1]. More recently, it has been widely discussed in the context of cooling our own planet, in an attempt to mitigate effects of human-induced global warming (e.g., [2–5]). The basic underlying concept is extremely simple – a reflective or deflecting substance or substances are placed between the Earth and the Sun in order to reduce the intensity of incoming solar radiation at the top of the Earth's atmosphere. The amount of reduction in solar radiation would be chosen to offset, or partially offset, surface warming induced by increases in greenhouse gases in the Earth's atmosphere.

The apparently alluring idea that a sunshade could perfectly offset greenhouse-gas-induced global warming is, perhaps unfortunately, an oversimplification. A sunshade positioned in space between the Earth and the Sun would reduce the effective strength of the Sun, resulting in an absolute change in the local solar forcing at the top of the Earth's atmosphere proportional to the local solar input, meaning that high latitudes and winter seasons receive less solar energy decrease than low latitudes and summer seasons (see Fig. 2.1). However, the radiative forcing due to increased greenhouse gases is more homogenous seasonally and latitudinally. As such, although the *global annual mean* greenhouse gas forcing could be exactly canceled by a solar shield, in such a "globally corrected" case the tropical and summer regions would be overcompensated, and high latitude and winter regions would be undercompensated. This would result in a surface temperature pattern of a globally corrected geoengineered world which, compared to modern, would be colder in the tropics than in the high latitudes. Along with this imperfect cancelation of temperature, other aspects of the Earth system would also remain unmitigated, such as changes to the hydrological cycle, as well as impacts resulting directly from the high CO_2, such as ocean acidification.

This entry focuses on the climatic effects (both desired and undesired) of placing sunshades in space. It also touches very briefly on some of the engineering considerations associated with the manufacture and launch of such a system. The substantial governance, political, and ethical considerations are not discussed here. Instead, the reader is referred to Virgoe [21], Blackstock and Long [7], and Corner and Pidgeon [8] for discussion of these more qualitative, but nonetheless important, issues.

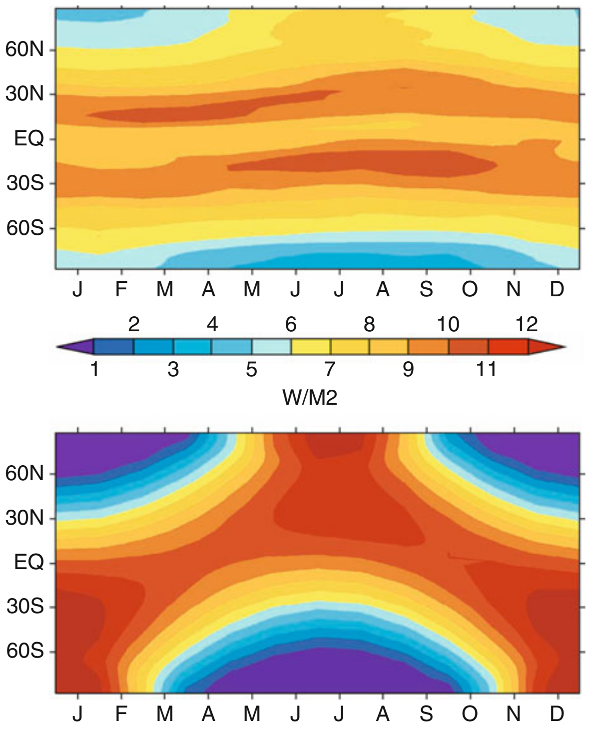

Fig. 2.1 Change in net long-wave radiative flux at the tropopause when CO_2 is quadrupled (*top panel*) with respect to the Control case and the reduction in incoming solar radiation (*bottom panel*) needed to compensate this forcing. Both values (W m^{-2}) are zonally averaged as a function of time of year. Change in solar radiation has a latitudinal and seasonal pattern markedly different from the radiative forcing of CO_2 (Adapted from [6], Fig. 2.1)

Modeling the Efficacy of Sunshades

Background

Because of the incredible complexity of the Earth system, and the expense and potential risks of carrying out large-scale field studies, probably the only way that the success and possible side effects of sunshade geoengineering can be assessed, at least initially, is through numerical climate modeling. Climate models, also known as “General Circulation Models,” or GCMs, consist of a numerical representation of our best understanding of the Earth system. In the atmosphere, they typically consist of a “dynamical core” which solves an approximation to the fundamental equations of motion of a perfect gas on a rotating sphere, a representation of radiative processes across a range of wavelengths from the solar to the infrared, and a set of “parameterizations,” which represent the large-scale effect of processes which occur at too small a scale to be resolved by the dynamical core, such as small-scale atmospheric waves, turbulence, processes associated with clouds, surface processes such as evaporation, and other aspects of the hydrological cycle. These atmospheric models can either have the temperatures of the ocean surface prescribed as boundary conditions, or can use a simple “slab” representation of the ocean in which the ocean interacts thermodynamically with the atmosphere (e.g., warming up if the atmosphere warms).

The last decade has also seen the development of coupled atmosphere-ocean models, which, as well as the atmosphere, also solve equations related to the fluid flow of the oceans. Given an initial condition (e.g., a static atmosphere and ocean, or the ocean–atmosphere state on a particular historical day since the advent of dense networks of observations) and a set of appropriate boundary conditions (such as the Earth’s topography and bathymetry and land-surface characteristics, and atmospheric gas composition), a model will typically solve the equations in the dynamical core and associated parameterizations, and increment the state of the atmosphere forward in time (typically 15 min to 1 h, depending on the spatial resolution of the model – high-resolution models require short timesteps to maintain numerical stability). If the boundary conditions remain fixed over time, then the model will eventually (typically years to decades for an atmosphere-only model, centuries to millennia for an atmosphere-ocean model) reach a quasi-equilibrium, where dynamic weather systems are superimposed on an equilibrium circulation of the atmosphere-ocean system. In this case, the initial condition of the model becomes unimportant (unless there are multiple equilibrium states of the system for the given boundary conditions).

How can these models be applied to sunshades in space? In a typical numerical experimental design, three model simulations are carried out with three different sets of boundary conditions. Firstly, a “modern” (or “control” or “preindustrial”) simulation is carried out, in which the boundary conditions are set as those of the modern era (or alternatively pre-industrialization values for atmospheric gas composition). Secondly a “perturbed” or “future” simulation is carried out, in which greenhouse gas concentrations are set at elevated concentrations (e.g., twice or four times preindustrial or modern values). Thirdly, a “geoengineered” simulation is carried out, in which the greenhouse gas concentrations are elevated and in addition the strength of the Sun’s solar output (the “solar constant”) is reduced. The reduction of solar constant acts as an approximation to the effect of a sunshade in space. The magnitude of the solar constant reduction is usually chosen so as to balance as closely as possible the global annual mean increase in surface air temperature caused by the elevated greenhouse gas concentrations. An alternative experimental design consists of a transient time-varying simulation, in which greenhouse gas concentrations are slowly increased in the “future” simulation, and a corresponding slow increase in the strength of the solar shield is applied in the “geoengineered” simulation.

Results

The first numerical model study of the impacts of geoengineering was carried out by Govindasamy and Caldeira [2]. Using an atmospheric GCM and a “slab” ocean model, they carried out three equilibrium simulations, as outlined above. They found a cooling in the tropics (20°S–20°N) in their geoengineered simulation compared to their control simulation, and a warming outside these regions. However, because of the relatively short length of the simulation (the climatologies were calculated over only 15 years of model time), only a small fraction of the temperature changes in their geoengineering simulation compared to their modern simulation were deemed statistically significant at a 95% confidence limit. Coupled with their use of a "slab" ocean model compared to a full atmosphere-ocean GCM, some of their other results (e.g., they observed an increase in sea ice in their geoengineered simulation compared to their control, and little change in the hydrological cycle) remained somewhat ambiguous. However, this paper was certainly pioneering, and inspired a series of subsequent studies which used a very similar methodology.

Govindasamy et al. [6] carried out a follow-on study, which increased the forcing to a fourfold increase in greenhouse gas concentration. This resulted in a larger signal to analyze, and, as well as confirming their earlier results regarding temperature changes, also resulted in a more physically realistic decrease in sea ice in their geoengineering simulation compared to their control. They also noted that this form of geoengineering, although doing a relatively good job of returning tropospheric temperatures back to modern levels, does little to counteract the cooling in the stratosphere associated with the warming in the troposphere. There was also a decrease in evaporative water flux from the ocean to the atmosphere in the tropics, associated with the cooler sea surface temperatures. However, they noted that all their results, and especially those associated with sea ice, should be regarded with some caution due to their use of a "slab" ocean model and lack of dynamics in the sea-ice scheme.

This issue was partially addressed by the study of Matthews and Caldeira [5]. They used a model with a representation of ocean dynamics, but due to computational constraints used a simplified representation of the atmosphere compared with Govindasamy and Caldeira [2]. They carried out a set of "transient" geoengineering simulations. Because their model was relatively computationally efficient, they were able to carry out long simulations and obtain statistically meaningful results. Their results largely agreed with those of previous studies regarding temperature change, but were very different in terms of precipitation. Matthews and Caldeira [5] found a widespread decrease in continental precipitation in a geoengineered world compared to modern, in particular over the rainforest regions of Amazonia, Central Africa, and South East Asia. They attributed this to decreased evapotranspiration in a high-CO_2 world, as plants used water more efficiently. Matthews and Caldeira [5] also addressed the question of the "safety" of sunshade geoengineering. In particular, several of their scenarios included a simulated catastrophic failure of the sunshade, such that the solar constant was instantaneously increased back to its normal value, with CO_2 levels still high. In this case, they found an extremely rapid warming, up to 20 times greater than the current anthropogenic warming. However, as with previous work, there remained some uncertainty in the validity of some of the results (in particular, the large reduction in precipitation in the geoengineered case) due to the lack of complexity in the atmospheric component of their model.

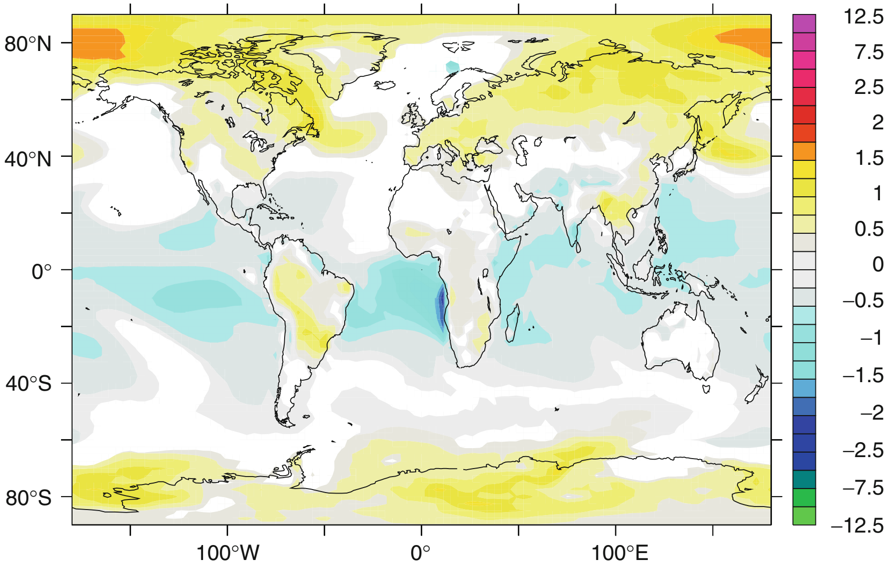

Fig. 2.2 Change in near-surface air temperature (°C) in a sunshade geoengineered world compared to modern, as predicted by a coupled atmosphere-ocean General Circulation Model. Regions where the difference is not statistically significant at a 95% confidence limit, as given by a Student *T* test, are masked out in white (Adapted from [4], Fig. 2.2)

The first study to use a fully coupled atmosphere-ocean climate model to investigate sunshade geoengineering was that of Lunt et al. [4]. They also carried out long simulations with averages calculated over 60 years. In general terms, their temperature estimates for the "sunshade world" were similar to previous, but with some new features, such as a maximum in cooling off the west coast of tropical Africa, associated with increased ocean upwelling in the geoengineered case, and maximum warming in the Arctic north of the Bering Strait, associated with a loss of sea ice (see Fig. 2.2). They also found new results in terms of precipitation, with a global mean decrease in precipitation predicted (in agreement with Matthews and Caldeira [5]), but instead of maximum reductions over continents, they found maximum reductions over the tropical oceans, in a regional pattern which correlated with that of temperature. The use of a fully coupled model also allowed them to investigate changes in El Nino Southern Oscillation (ENSO). They found a significant decrease in the amplitude of ENSO variability in sunshade world relative to modern, associated with a decrease in the tight coupling of atmosphere and ocean feedbacks due to the cooler tropics, but no significant change in ENSO frequency. They also found that the geoengineered world had a slightly more vigorous ocean circulation than the control, associated with a decrease in the intensity of the hydrological cycle, and decreased poleward moisture transport.

This study was followed up by Irvine et al. [3], who used the same model, but investigated a range of "strengths" of sunshade geoenginering, from 100% (which exactly balances the global annual mean temperature change associated with a greenhouse gas concentration increase), to 0% (no geoengineering). They also looked in more detail at the regional patterns of change following sunshade geoengineering. For example, they found that, relative to modern, the USA mainland region experiences a +8% increase in precipitation given 0% geoengineering, and an 11% decrease in precipitation given 100% geoengineering. According to their results, to achieve a precipitation rate close to that of modern, the USA would "choose" a sunshade of strength 40–50%. However, the east China region experiences precipitation back at modern levels with 100% geoengineering. The possible political implications are considerable. They also investigated the effects of sunshade geoengineering on croplands and densely populated regions, and found that in order to obtain modern average values of precipitation in cropland regions would require 75% geoengineering, whereas in urban areas it would require 85% geoengineering. Although this study highlighted the very regional impacts of geoengineering schemes, it should also be noted that no climate model is perfect, and in particular precipitation remains one of the variables which shows the largest inter-model spread. As such, the exact predictions of "ideal" geoengineering levels presented in Irvine et al. [3] should be regarded with some caution.

Several other studies have looked at the implications of sunshade geoeingineering on other aspects of the Earth system. Govindasamy et al. [9] looked at the impact of geoengineering on the biosphere. They used a coupled atmosphere-biosphere model with a slab ocean to carry out the classic three equilibrium geoengineering simulations. They found that the decrease in solar energy in the geoengineered world had very little effect on net primary productivity (NPP) by the biosphere, and instead that the CO_2 increase relative to modern resulted in almost a doubling of NPP. Their model did neglect some possibly important factors such as changes to nutrient cycles in the sunshade world. However, these are likely to be minor compared to the zeroth order result of increased biomass in the geoengineered world compared with modern.

Irvine et al. [10] addressed the possible mitigative potential of sunshade geoengineering for sea-level rise. This question was motivated by the "residual" Arctic warming seen in all of the sunshade geoengineering simulations. Would this residual warming be enough to significantly affect the Greenland ice sheet, and lead to sea-level rise? To address this question they used an offline ice sheet model, which, given fields of temperature and precipitation, calculates the surface mass balance (accumulation vs. melt) and flow of an ice sheet, to obtain an ice sheet geometry that is in equilibrium with the temperature and precipitation. They compared the ice sheets predicted to be in equilibrium with the "control," "future," and "geoengineered" climates from GCM simulations, and found that the "future" climate produced a Greenland ice sheet which was almost completely melted, with only small ice caps remaining on the high-altitude or high-accumulation regions in the east and south of Greenland, equivalent to a sea-level rise of 6.4 m. However, the "geoengineered" climate, despite the residual Arctic warming, was almost identical