Modeled Changes to the Earth's Climate under a Simple Geoengineering Scheme and Following Geoengineering Failure

by

Michael John Shumlich

B.Sc. University of Victoria, 2010

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Supervisory Committee

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Geoengineering is the intentional alteration of the Earth's climate system. The international Geoengineering Model Intercomparison Project (GeoMIP) seeks to identify the potential benefits and side effects of geoengineering on the Earth's climate.

This thesis examines the first two experiments from the contribution of the Canadian Centre for Climate Modelling and Analysis to GeoMIP. In the first experiment (G1), atmospheric carbon dioxide concentrations are quadrupled and the solar constant is reduced to offset the increased greenhouse gas forcing. In the second experiment (G2), atmospheric carbon dioxide concentrations are increased at the rate of 1% per year and the solar constant is incrementally reduced to offset the greenhouse gas forcing. In concert with these experiments, results from two other experiments were analyzed, one in which the atmospheric greenhouse gas concentrations are quadrupled one in which they are increased at the rate of 1% per.

The results obtained are in broad agreement with earlier work, showing that solar radiation management geoengineering schemes can prevent an increase in mean global surface temperature as atmospheric carbon dioxide concentrations increase. Though the mean global temperature remains constant while geoengineering is employed, there are regional and zonal differences from the control climate, with high latitude warming and cooling in the tropical and subtropical regions. In particular, the meridional temperature gradient is reduced compared to that of the control climate. The G2 experiment was very similar to the G1 experiment in terms of the spatial surface temperature changes, though the changes seen in the G2 experiment were less pronounced and the regions of statistical significance were smaller.

During the geoengineering period, seasonal changes and a statistically significant decrease in global precipitation, particularly over the ocean were apparent in the G1 run. As with temperature, the spatial pattern of precipitation changes during the geoengineering period for G2 are similar to the same period in G1, but reduced in magnitude. However, most of the spatial changes to precipitation in the G2 experiment during geoengineering deployment fail to be statistically significant.

Following geoengineering termination, the G1 experiment responds rapidly, with surface and ocean temperatures, NH and SH summer sea ice volume, AMOC transport volume and global precipitation following the same time evolution and reaching those same values found in the $4 \times CO_2$ experiment's first 10 years. Following geoengineering failure, the G2 run also experiences rapid climate change in all of the variables studied, but does not approach the first 10 years of the $1\%CO_2yr^{-1}$ experiment, because the forcings are quite different in the two runs.

Taken together, these results suggest that, while geoengineering to reduce incoming solar radiation could offset the global temperature increase due to increased atmospheric greenhouse gas concentrations, there would be regional warming and cooling, as well as both global and regional impacts on the hydrological cycle. These results also suggest that, should geoengineering suddenly stop, the Earth's climate would react immediately, with rapid changes in nearly all of the climate variables examined.

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1 Introduction

1.1 Outline

This introductory section will provide the context for this thesis. First, the current anthropogenic perturbation of the Earth's climate system and the projected changes to the Earth's climate system assuming continued emission of greenhouse gases (GHG), along with the consequent impacts will be outlined. Following this, there will be a brief outline of the types of climate engineering schemes that have been put forth. Special attention will be given to methods involving stratospheric sulfate aerosols because they are one of the cheaper and easier methods of solar radiation management geoengineering and the international Geoengineering Model Intercomparison (GeoMIP) experiment, data from which this thesis analyzes, was designed in part to evaluate the efficacy and risks of stratospheric sulfate aerosol geoengineering. Given the nature of this research, something must be said about the ethics of deliberately affecting the climate in such a manner, so some background on the current ethical discourse will be provided. Finally, the GeoMIP experiment will be outlined and the results of relevant (prior) experiments will be discussed.

1.2 Anthropogenic Climate Change

In their Fourth Assessment Report (AR4) the Intergovernmental Panel on Climate Change (IPCC) found that with "very high confidence," the increase in atmospheric GHG concentrations due to anthropogenic emission are affecting the Earth's climate (Meehl et al. 2007). A full discussion of the attribution literature which the IPCC report assessed and the subsequent attribution literature is beyond the scope of this thesis. The fact that anthropogenic land use changes and GHG emissions are affecting the Earth's climate is here assumed and the interested reader is directed to the IPCC report (Meehl et al., 2007) for background information. AR4 detailed a number of ongoing changes to the Earth's climate system, projected a variety of future changes to the Earth's climate system given various emissions scenarios and discussed the potential impacts of these changes on both human societies and ecosystems. These will be discussed briefly here because the changing climate and its potential impacts provide motivation for research into geoengineering options.

Among the observations presented in the contribution of Working Group 1 (WG1) of the AR4 are: over the period 1850-1899 to 2001-2005, global average surface temperatures have increased by 0.76 ± 0.19 °C (Trenberth et al., 2007); there has been an increase in drought duration and intensity since the 1970s (Solomon et al., 2007); heavy precipitation events over land areas have become more frequent; ocean pH levels have been dropping and are presently at 0.1 units lower than pre-industrial values (Bindoff et al. 2007), roughly a 30% increase in H^+ ions or "acidity"; temperatures have increased by up to 3°C at the top of the Arctic permafrost layer (Lemke et al., 2007); and both mountain glaciers and snow cover have decreased globally (Solomon et al., 2007). Other changes include: effects on the disturbance regimes of forests, increased heat-related mortality in Europe, changes to infectious disease vectors and effects on hunting and travel in the Arctic (Parry et al. 2007).

The projections used in AR4 are based on various emissions scenarios. For example, emissions scenario A1B assumes a balanced emphasis on both fossil and non-fossil energy sources and finds a likely range of temperature change, for the period of 2090-2099 relative to the period of 1980-1999,of 1.7 to 4.4 °C (Meehl et al. 2007), whereas the A1FI scenario assumes an emphasis on fossil energy sources and finds a likely temperature range, for the same period, of 2.4 to 6.4 °C (Meehl et al. 2007).

1.3 Impacts of Anthropogenic Climate Change

A variety of projected impacts are outlined in Working Group II's contribution to AR4, among them: a 10-30% decrease of water availability in some dry regions in the mid latitudes and tropics, as well as a reduction in water availability for those regions which rely upon melt water from glaciers; an increase in the extent of drought-affected areas; an increase in heavy precipitation events and flooding as well as storm surge events and coastal erosion; 20-30% of plant and animal species are expected to be at risk from extinction, should global temperature increases exceed 1.5 to 2.5 °C; low latitude crop yields are expected to decrease and ocean acidification is expected to negatively affect marine calcifying organisms, such as corals, coccolithophorids and mollusks (Parry et al. 2007).

Given that industrial GHG emissions have been deemed largely responsible for the above changes, there have been efforts to quantify what would constitute dangerous anthropogenic interference (DAI) in the global climate system. The notion of what constitutes 'dangerous' is normative and hence, relative to the values and needs of various geopolitical stakeholders a variety of suggestions have been put forth (Ramanathan and Feng 2008; Schneider and

Mastrandrea, 2005). While there is significant variability in what constitutes DAI, all of the suggestions thus far fall within the range of 1 °C to 3 °C global mean warming (Ramanathan and Feng 2008).

1.4 Geoengineering: Motivation

Global anthropogenic carbon dioxide emissions show no signs of decreasing; in fact, they have been more or less keeping pace with the fossil fuel intensive A1FI scenario (Figure 1.1.).

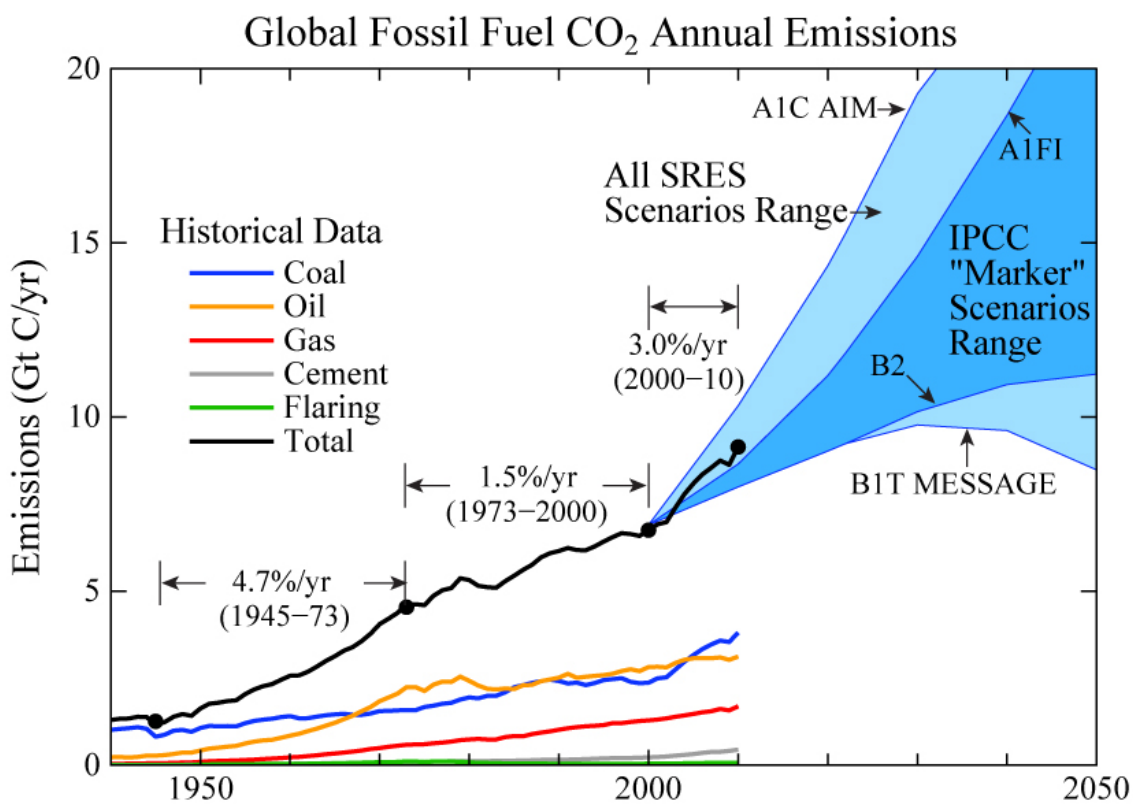

Figure 1.1: Annual CO_2 Emissions
The above is an updated figure from Hansen (2003) using data from Boden et al. (2011). Retrieved from: <http://www.columbia.edu/~mhs119/Emissions/>, June 2012.

Plainly, emissions reductions efforts have thus far been ineffective. A full discussion of why such efforts have been ineffective is beyond the scope of this paper, but, in short, the causes range from increasing emissions from emerging economies (Friedlingstein et al., 2010) to a well documented corporate lobbying and misinformation campaign directed at preventing or delaying emissions reduction legislation (see for example: Hoggan and Littlemore, 2009 and Oreskes and Conway, 2010). So, while it seems clear that the safest method of preventing DAI on the Earth's climate system is to reduce emissions, political inertia seems such that, at the present moment, sufficient emissions reductions are not forthcoming (Shepard et al., 2009 and Gardiner, 2010).

Given all of the above, there have been calls for an examination of various methods for the purposeful alteration of the Earth's climate system (i.e. geoengineering), to respond to and mitigate the worst potential effects of anthropogenic climate change (Shepard et al., 2009; Blackstock et al., 2009). It is important to note that these geoengineering proposals are offered as being complementary to emissions reductions (Blackstock et al., 2009). This is because certain schemes do not address all of the problems associated with anthropogenic climate change (e.g. orbital reflectors don't address ocean acidification) and even those schemes that do address all of the problems bring with them their own associated risks or challenges (e.g. how to sequester all of the carbon collected by carbon scrubbers).

1.5 Proposed Geoengineering Schemes

Geoengineering schemes can be generally divided into two categories: carbon dioxide removal (CDR) methods, which attempt to directly remove carbon dioxide from the atmosphere, and solar radiation management (SRM) methods, which attempt to reduce or reflect the amount of incoming solar radiation that reaches the Earth's surface (Shepard et al., 2009; Blackstock et al., 2009).

1.6 Carbon Dioxide Removal Schemes

1.6.1 OUTLINE

CDR methods all rely upon chemical reactions to remove carbon dioxide from the atmosphere. CDR methods vary widely in their approaches, using land management, living organisms and chemical-filled air collectors to draw down carbon. The main schemes suggested are: carbon scrubbing, aforestation and reforestation, biochar methods, enhanced weathering and ocean fertilization (Shepard et al., 2009).

1.6.2 CARBON SCRUBBING

Carbon scrubbing methods involve passing air containing carbon dioxide through chambers (Stolaroff et al., 2008), or over pools (Dubey et al., 2002), wherein the air is exposed to chemicals that react with the carbon dioxide in the air, such as the following reaction with sodium hydroxide:

$$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O \quad \textbf{Equation 1.1}$$

The carbon is then captured and the air with lower carbon dioxide concentrations is returned back to the atmosphere (Shepard et al., 2009; Stolaroff et al., 2008).The captured carbon is then stored, for example, by liquefaction and injection into deep geological strata, or in the form of a stable rock carbonate, such as magnesite ($MgCO_3$) (Lal, 2008). For example, the carbonation reaction using olivine and leading to the sequestration of carbon in magnesite is as follows:

$$Mg_2SiO_4 + 2CO_2(g) \rightarrow 2MgCO_3 + SiO_2 \quad \textbf{Equation 1.2}$$

The problem is that such schemes are viewed as expensive, in the range of $100 per ton of carbon dioxide (Stolaroff et al., 2008) and potentially require large areas. For instance, using Stolaroff's scheme, an area of roughly 0.58 square kilometers is needed to capture 1 Mt of carbon per year. Given that current global emissions are just shy of 9 Gt per year and increasing (Boden et al., 2010) offsetting these emissions would require an area of at least roughly 5200 square kilometers—for comparison, the Alberta Tar Sands have a surface minable area of ~4890 square kilometers (Lee, 2009)—and the cost of such a geoengineering scheme would be roughly 900 billion dollars per year.

1.6.3 REFORESTATION AND AFFORESTATION

Land management consists of reforestation and afforestation. Noting that terrestrial ecosystems draw down about one-third of the carbon dioxide emissions from fossil fuel use (Shepard et al., 2009) and that land use change accounts for roughly a fifth of anthropogenic GHG emissions (Shepard et al., 2009), the objective is to (at least partially) restore these ecosystems, increasing the drawdown of carbon. It should be noted that reforestation and afforestation practices have other benefits, such as providing habitats for various animal species and, in the tropics and subtropics, cooling through evapotranspiration (Betts, 2000), though it might also be partially offset by albedo-induced warming (Kirschbaum et al., 2011). Unfortunately, the demand for land limits this strategy. The Royal Society has indicated that a realistic target, by 2030, for the combined efforts of limiting deforestation, while committing to afforestation and reforestation, would be 0.4 to 0.8 Gt per year, or between 2% to 4% of emissions over this period (Shepard et al., 2009).

1.6.4 BIOCHAR METHODS

The thermochemical decomposition of biomass in anoxic conditions at high temperature is known as pyrolysis and the product, biochar (charcoal), is a stable compound which can reside in soil, trapping roughly 50% of the carbon from the pyrolized biomass, for thousands of years (Shepard et al., 2009). Biochar is porous, with a large surface area and efficient in retaining nutrients and water in soil. Its use in agriculture has been suggested as a method for sequestering carbon. However, the effectiveness, costs and wider impact of increased biochar production for this purpose has yet to be assessed (Shepard et al., 2009).

1.6.5 ENHANCED WEATHERING

The weathering of certain rocks, such as silicates, carbonates and lime can also act to draw down carbon. For example, the reaction that occurs when silicate minerals react with carbon dioxide to form carbonate is,

$$CaSiO_3 + CO2 \rightarrow CaCO_3 + SiO_2 \qquad \textbf{Equation 1.3}$$

These schemes range from the addition of olivine in soils to adding lime to the ocean (Shepard et al., 2009). One major hurdle for enhanced weathering schemes is that they often require the mining of minerals on a vast scale, which will be energy intensive and potentially quite harmful to the environment. It should be noted also that these reactions are quite slow; currently carbon dioxide is being drawn down at the rate of 0.1 Gt per year (Shepard et al., 2009).

1.6.6 OCEAN FERTILIZATION

Proposals have also been made to increase the strength of the ocean's biological carbon pump, which draws down roughly 22 Gt of carbon per year from the atmosphere through the sinking of particulate biological material (Shepard et al., 2009). These schemes call for either nutrients such as iron, nitrogen or phosphorous to be deposited directly on the ocean's surface, or deep, nutrient rich water to be pumped to the surface, increasing net primary productivity and thereby drawing down carbon (Shepard et al., 2009). It is important to note that the carbon must then be drawn down to the deep ocean for sequestration. The overall efficiency of these schemes is still uncertain and there is the potential for unintended negative consequences for the ocean's ecosystems due to several causes, including depletion of nitrates, depletion of silicic acid, eutrophication and shifts in distributions of spatial macronutrients (Secretariat of the Convention on Biological Diversity, 2009; Gilbert et al., 2008).

1.7 Solar Radiation Management Schemes

1.7.1 OUTLINE

SRM proposals all attempt to offset temperature changes from anthropogenic climate change through reducing or reflecting incoming solar radiation. These schemes vary greatly in terms of cost, potential impact and technological requirements. The SRM proposals which deal with surface reflection are: ocean albedo alteration through microbubble generation, human settlement albedo modification and desert surface albedo modification. The SRM proposals which deal with reducing incoming solar radiation can be divided into space-based reflectors, cloud albedo enhancement and stratospheric aerosols. It should be noted that solar radiation management schemes will primarily affect temperature and, because they don't act to reduce atmospheric CO_2 concentrations, don't address the quite serious issue of ocean acidification, which is caused by the ocean's increased uptake of CO_2 due to elevated atmospheric concentrations of CO_2 from anthropogenic emissions.

1.7.2 SURFACE ALBEDO MODIFICATION

Ocean microbubble albedo modification uses micron scale hydrosols to reflect incoming solar radiation incident on the ocean's surface. Micron scale bubbles are suggested for two reasons: because, from Mie theory, the backscattering efficiency of the microbubble is proportional to the inverse of the bubble's radius and, by Stokes's law, microbubbles take much longer to surface and burst than larger bubbles (Seitz, 2011). Seitz (2011) found that, assuming microbubbles could produce an overall global albedo increase of ~0.031, they could reduce global mean temperature by ~2.7 °C. The bubbles could be generated by utilizing the shipboard compressors, which currently reduce hull drag by generating macrobubbles, to generate microbubbles that will increase the surface water's albedo in the ship's wake (Seitz, 2011). Potential shortcomings of this proposal include the fact that bubbles of the required size tend to be unstable, requiring surfactants of some sort to increase their lifetimes and also, that research needs to be done to determine how they might affect marine ecosystems and carbon drawdown (Seitz, 2011).

Another suggestion has been increasing the surface albedo of human urban developments, through such measures as painting roofs white. However, with an estimated cost of 300 billion dollars per year and an estimated reduction of 0.01 Wm^{-2} to 0.2 Wm^{-2}, it is likely not economically worthwhile to do so (Shepard et al., 2009).

Instead of increasing the albedo of human urban developments, agricultural lands and grasslands can be targeted. The albedo of such lands varies, in large part due to the properties of the leaves and canopies of the resident vegetation (Ridgwell et al., 2009; Shepard et al., 2009). Hence, plant choice for such regions can affect the albedo. A modeling experiment has shown a possible 1 °C reduction of temperatures in North America and Europe due to such a scheme (Ridgwell et al., 2009; Shepard et al., 2009) or an overall radiative forcing to the global mean annual energy budget of -1 Wm^{-2} (Lenton and Vaughan, 2009; Shepard et al., 2009). Research into the cost and potential effect on crop yields remains to be done (Shepard et al., 2009).

Desert surface albedo modification schemes involve covering the desert with polyethylene-aluminum reflectors in order to increase the Earth's albedo. While this might achieve a radiative forcing of -2.75 Wm^{-2}, it does so with the significant risk of significant adverse ecological impacts over the regions affected—for example, through putting large quantities of polyethylene-aluminum into the ecosystems—and comes with a price tag on the order of several trillion dollars per year (Shepard et al., 2009).

1.7.3 SPACE-BASED REFLECTORS

Space-based solar radiation management schemes involve placing reflectors, potentially in the form of disks, mirrors and threads, between the Earth and the sun—either in orbit around the Earth or at the L1 Lagrange point[1]—to reduce the amount of incoming solar radiation and hence, offset the warming from anthropogenic greenhouse gas emissions (Angel, 2006, Shepard et al., 2009). The scale of such a project is staggering, even by the standards of geoengineering projects. For instance, the proposals include: "a swarm of around ten trillion extremely thin high specification refracting disks each about 60 cm in diameter, fabricated on Earth and launched into space in stacks of a million, one stack every minute for about 30 years," assembling a reflector on the moon from a hundred million tons of lunar glass, or fabricating trillions of 0.5 m reflecting disks in space, from materials garnered from the mining of near Earth asteroids (Shepard et al., 2009). Though, were such a proposal to be implemented and the amount of incoming solar radiation decreased, the climate system should respond rapidly to offset anthropogenic global warming (Matthews and Caldeira, 2007). However, this plan might not be desirable because it would take decades to implement, at very high costs and rapid warming would ensue should the system be seriously compromised (Shepard et al., 2009).

1.7.4 CLOUD ALBEDO ENHANCEMENT

Cloud albedo enhancement geoengineering is intended to work by injecting sea spray into the atmosphere, thereby increasing the number of cloud condensation nuclei in marine clouds and,

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[1] The L1 Lagrange point is one of five positions in a three-body gravitational dynamics problem, in which an object of relatively small mass can be placed in a system with two orbiting bodies of much larger mass, in a position such that the gravitational forces and force due to orbital motion (i.e. centripetal force) acting on the smaller body balance each other. Hence, the body with negligible mass can orbit the bodies at a fixed distance, remaining approximately stationary with respect to the two larger bodies in a reference frame which rotates about the combined center of mass of the larger bodies, with the same angular velocity as the two co-orbiting bodies. Loosely, in the Earth-Sun system, a mass orbiting at the L1 Lagrange point would always be in between the Earth and the sun. It should be noted that this is an unstable Lagrange point and an object placed here requires constant correction to prevent it from drifting away from the L1 Lagrange point. (For further reading, see Chapter 13 of Seeds (2007) and the more thorough treatment in Chapter 13 of Guidry (2012).)

because clouds with a large number of small nuclei have a higher albedo than clouds with a small number of large nuclei (this is the so-called Twomey effect), the hope is that there will not only be an increase in cloud cover, but an increase in cloud cover consisting of clouds with a high albedo (Shepard et al., 2009). This would be accomplished through a fleet of radio controlled, wind powered marine vessels spraying water into the sky (Salter et al., 2008, Shepard et al., 2009). Initial model results from Latham et al. (2008) suggested that cloud albedo geoengineering could offset the global mean positive radiative forcing due to anthropogenic greenhouse gas emissions. The spatial change in radiative forcing at the top of the atmosphere from their work is shown below (Figure 1.2). However, these initial model results assumed nearly uniform cloud drop fields over the oceans and recent model results with the global aerosol model GLOMAP show that a variety of processes, including scavenging by precipitation, wind speed, atmospheric transport and deposition would make such a uniform field difficult to achieve in practice (Korhonen et al., 2010). Further, the global scale models that have been used to study the problem to date lack the resolution to resolve emissions, transport and cloud microphysics on the scale of individual cloud cells. Hence, more research, with large eddy cloud resolving models, is needed to ascertain whether this geoengineering scheme can truly be effective (Korhonen et al., 2010).

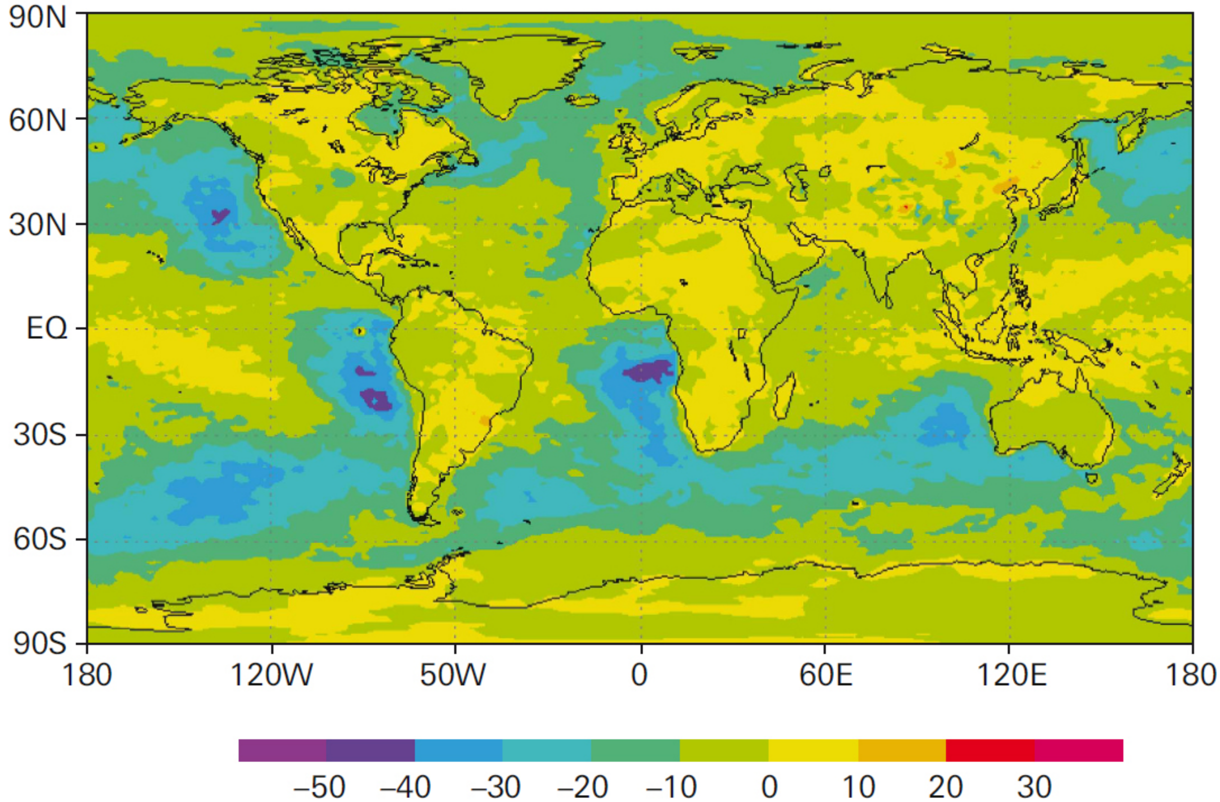

Figure 1.2: Effect of Cloud Condensation Nuclei Geoengineering
Above is the difference in the net radiation at the top of the atmosphere, in units of W/m^2, between a control simulation (with a volume of cloud condensation nuclei of $100/cm^3$) and a test run with a cloud condensation nuclei volume of $375/cm^3$ in regions of low-level maritime cloud (an extension of earlier results from Latham et al., 2008). Positive is taken to be in the downward direction.
(This has been taken from Shepard et al., 2009)

1.7.5 STRATOSPHERIC AEROSOL GEOENGINEERING: BACKGROUND

Inspired by the reductions in temperature following major volcanic interruptions, one of the more popular proposals has been using stratospheric aerosols to increase the Earth's albedo. Though aerosols other than sulfur, such as aluminum, have been proposed, this discussion will be limited to sulfate aerosols, though much of the basic theory applies to aerosols of differing composition.

Whenever a large volcanic interruption releases chemical species such as S, SO, H_2S, SO_2 and SO_3 into the stratosphere, these undergo a series of chemical reactions (Figure 1.3), forming sulfate aerosols that may ultimately reside in the stratosphere (Mather et al., 2004; Mills, 1996).

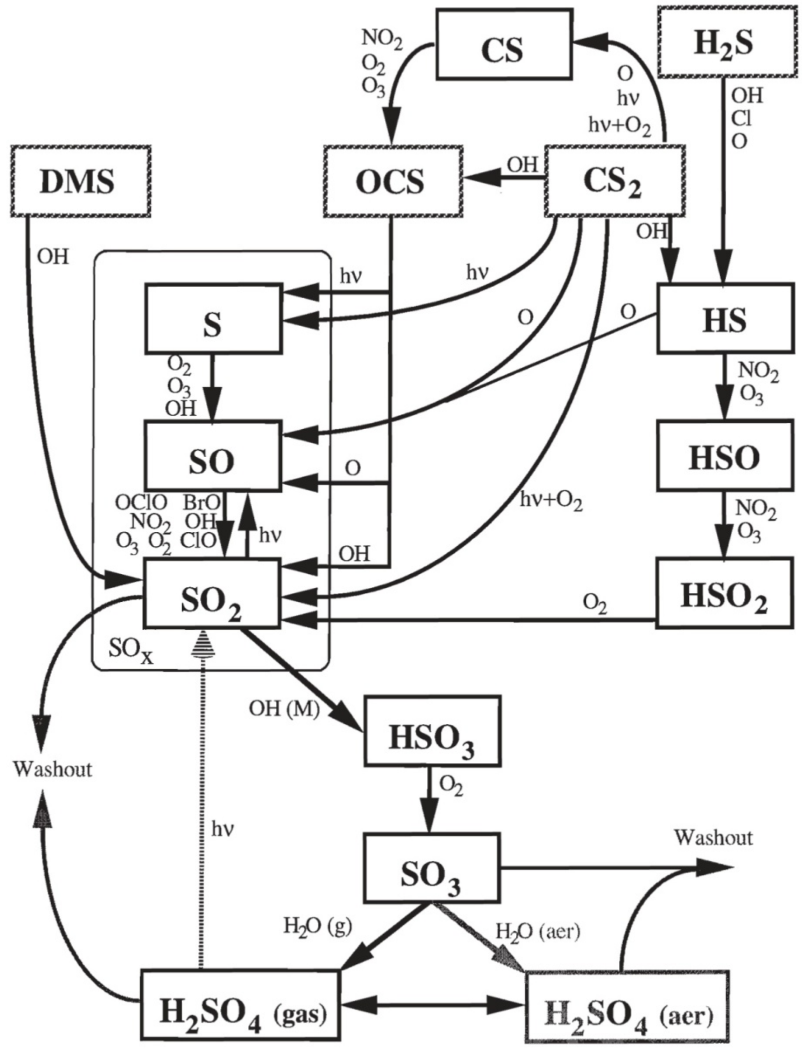

Figure 1.3: Chemical and Photochemical Sulfur Reactions
Atmospheric photochemical reactions of sulfur. (Taken from Mills, 1996.)

One simple example of such a reaction is:

$$H_2O + SO_3 \rightarrow H_2SO_4$$ **Equation 1.4**

Though most stratospheric sulfate aerosols are produced within the stratosphere, evidence suggests that H_2SO_4could be produced in the tropical tropopause region and ammonium sulfate and ammonium bisulfate aerosols might be convected into the stratosphere from storm systems (Teets, 1997). These aerosols then increase the planetary albedo, through directly reflecting incoming solar radiation (Crutzen, 2006). The size of the particles affects their scattering efficiency. From Mie theory, for a particle of diameter d, with refractive index, n, where the particle is much smaller than the wavelength of light to be scattered, λ, the scattering cross-section, σ is the Rayleigh scattering cross-section, $\sigma = \frac{2\pi^5 d^6}{3\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$, which gives a mass efficiency (loosely, the scattering per unit mass), ε, of $\varepsilon \equiv \frac{6\sigma}{\pi\rho\, d^3}$, where ρ is the density of the particle (Blackstock et al., 2009). For shortwave radiation ($\lambda \leq 5.0\mu m$), the ideal, mass-efficient particle size is approximately 0.1μm (Blackstock et al., 2009).

The schemes for injecting sulfate aerosols into the stratosphere generally involve putting the precursor to the desired aerosol, such as SO_2 gas, into the atmosphere and allowing chemical oxidation reactions in the atmosphere to generate the aerosols (Blackstock et al., 2009; Shepard et al., 2009). Various proposals exist for setting the precursors aloft; among them are chimneys, planes, balloons, missiles and naval guns (the interested reader is directed to Blackstock et al., 2009, for a discussion of the benefits and drawbacks of these approaches). Once in the atmosphere, the distribution of particles is determined by aerosol microphysics: the agglomeration due to nucleation between water and sulfuric acid or coagulation of particles can cause the aerosols to become too large, losing efficiency as scatterers and sedimenting out of the atmosphere quickly (Blackstock et al., 2009; Mills, 1996); as well as depositation through precipitation in the troposphere (Mills, 1996).

Model results have thus far shown that anthropogenic global warming can be offset by a reduction in incoming solar radiation (Ammann et al., 2010). Figure 1.4 and Figure 1.5 illustrate spatially to what extent the changes to temperature and precipitation from a doubled CO_2 concentration can be offset by solar radiation management, in an experiment which involved the reduction of the solar constant (Caldeira and Wood, 2008). Moreover, model results have suggested that, if global mean insolation can be modulated by latitude, then either zonal mean temperature or zonal mean precipitation changes under a doubling of carbon dioxide could be quite close to those in control conditions—though, if one optimizes to offset changes in temperature, then the offsetting of changes in the hydrological cycle degrades and vice versa (Ban-Weiss and Calderia, 2010). Also, stratospheric sulfate aerosol geoengineering ranks among the cheaper schemes yet suggested and can be done with technology available today, making it one of the more attractive geoengineering proposals to policy makers (Kravitz et al., 2010; Shepard et al., 2009).

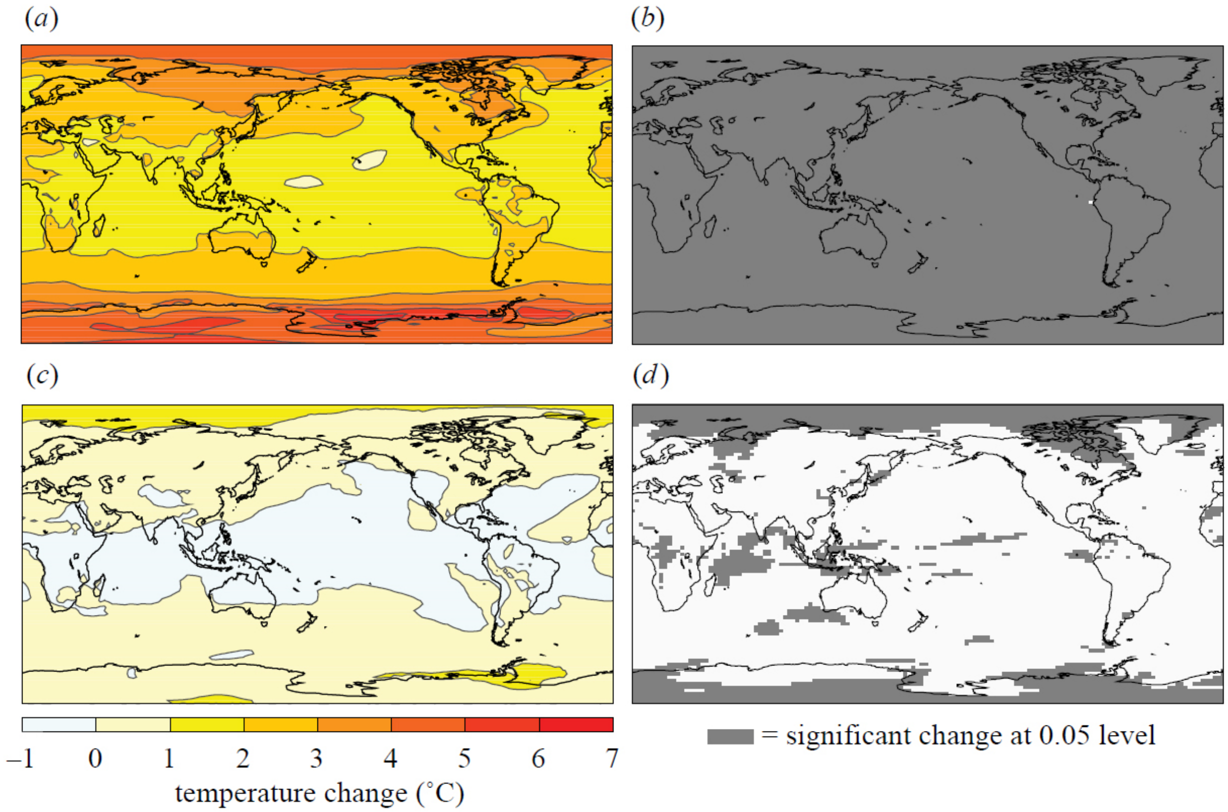

Figure 1.4: Geoengineering Temperature Change, Caldeira & Wood
Here: a) is the annual mean temperature anomaly in a 2 × CO_2 experiment, relative to a pre-industrial control (1× CO_2) climate; b) the grey colouring represents the area over which the temperature changes in (a) are statistically significant at the p=0.05 level; c) is the annual mean temperature anomaly in a 2 × CO_2 experiment, relative to a pre-industrial control climate, where the greenhouse forcing is being offset by a latitudinally varying reduction in the solar constant of average value 1.84%.; d) the grey colouring represents the area over which the temperature changes in (c) are statistically significant at the p=0.05 level.
(Caldeira and Wood, 2008)

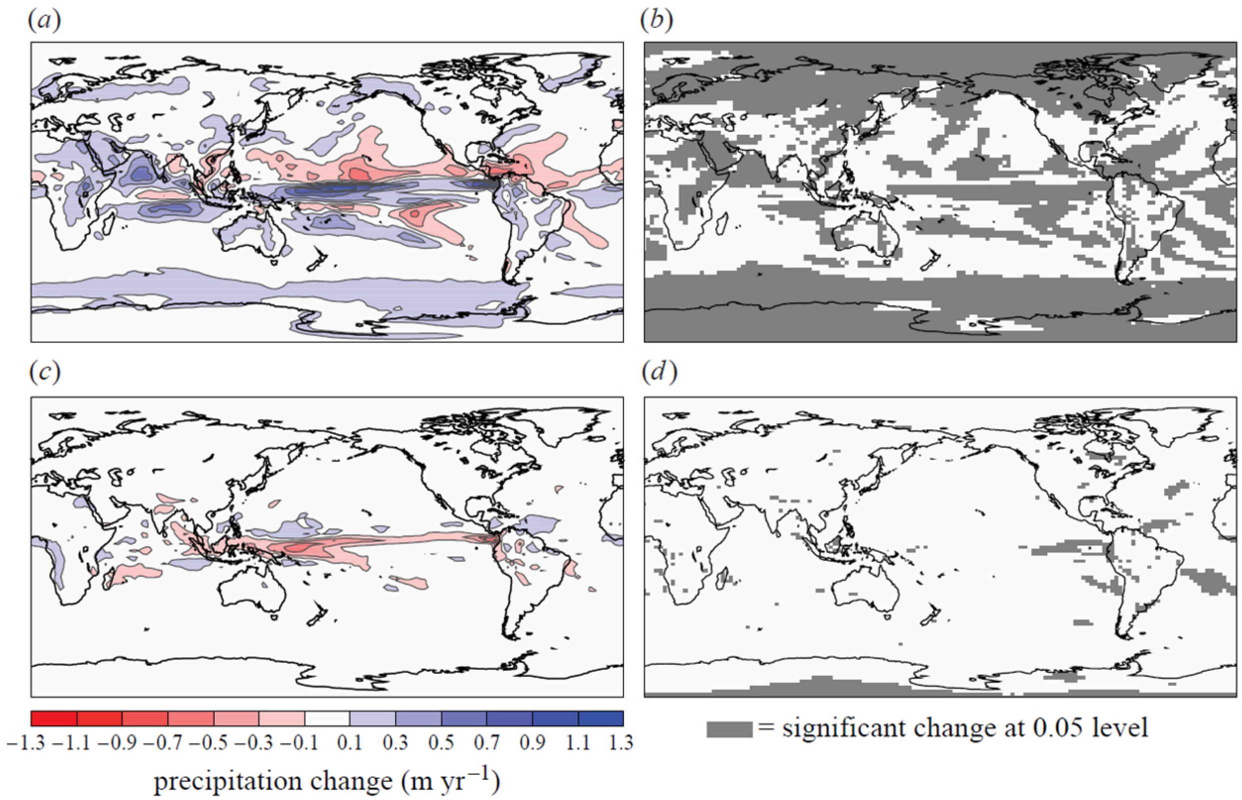

Figure 1.5: Geoengineering Precipitation Change, Caldeira & Wood
Here: a) is the annual mean precipitation anomaly in a 2 × CO_2 experiment, relative to a pre-industrial control (1× CO_2) climate; b) the grey colouring represents the area over which the temperature changes in (a) are statistically significant at the p=0.05 level; c) is the annual mean precipitation anomaly in a 2 × CO_2 experiment, relative to a pre-industrial control climate, where the greenhouse forcing is being offset by a latitudinally varying reduction in the solar constant of average value 1.84%.; d) the grey colouring represents the area over which the precipitation changes in (c) are statistically significant at the p=0.05 level.
(Caldeira and Wood, 2008)

1.7.6 STRATOSPHERIC SULFATE AEROSOL GEOENGINEERING: OZONE DEPLETION

A number of potential issues surround stratospheric sulfate aerosol geoengineering. The first one to be considered here is the potential effects of such a scheme on stratospheric ozone concentrations. Following large volcanic eruptions, there is a marked decrease in atmospheric ozone (Solomon, 1999). Similarly, a significant decrease has also been found in chemistry climate model data for a sulfate aerosol geoengineering experiment (Hackendorn et al., 2009). The atmospheric chemistry involved in ozone depletion as a result of sulfate aerosols is quite complex. In short, sulfate aerosols provide a surface on which chemical reactions involving mono-nitrogen oxides NO_X (specifically, N_2O_5 hydrolysis) locks up NO_X in a more stable species, HNO_3 (Heckendorn et al., 2009). As a result, less of the stable species $ClONO_2$ is produced, the amount of ClO_X increases and this enhances ClO_X ozone destruction (Heckendorn et al., 2009), through such processes as:

$$Cl + O_3 \rightarrow ClO + O_2$$ **Equation 1.5**

$$ClO + O \rightarrow Cl + O_2$$ **Equation 1.6**

Net Cycle: O and $O_3 \rightarrow 2O_2$ **Equation 1.7**

The interested reader is directed to Heckendorn et al., 2009 and especially Solomon, 2009 for a more thorough treatment of the relevant atmospheric chemistry.

1.7.7 STRATOSPHERIC SULFATE AEROSOL GEOENGINEERING: HYDROLOGICAL CYCLE IMPACTS

Another potential impact of stratospheric sulfate aerosol geoengineering is a change to the global hydrological cycle. Model results have shown that, under geoengineering schemes which reduce incoming solar radiation, global mean precipitation decreases (Bala, et al., 2008; Ammann et al., 2010). This happens because of the difference in the effectiveness of the forcing due to CO_2 emissions and the effectiveness of the forcing due to changing incoming solar radiation in affecting evaporation (Bala et al., 2008). It is instructive to see why this is so.

First, define the following terms: ΔLong and ΔShort shall be the differences in longwave and shortwave radiation at the Earth's surface; ΔLatent and ΔSensible shall be the differences in latent and sensible heat, respectively; F shall be the sum of shortwave and longwave forcings and the subscript r around a bracketed term shall signify that the attendant term represents only the response component of said term's change—e.g. $(\Delta Long)_r$ is the response component of the change in longwave radiation.

Next, following Bala et al., 2008, consider the time-mean, globally averaged surface energy flux differences between two arbitrary equilibrium states. These must sum to zero (or they would not be in equilibrium), so, assuming the convention that downward fluxes are positive for changes in radiation and negative for latent and sensible heat:

$$\Delta Long + \Delta Short - \Delta Latent - \Delta Sensible = 0$$ **Equation 1.8**

Now, consider the radiative forcings ΔLong and ΔShort in terms of their forcing and response components, grouping the forcing components together in the term F, as follows:

$$F + (\Delta Long)_r + (\Delta Short)_r - \Delta Latent - \Delta Sensible = 0$$ **Equation 1.9**

Bala et al. find that, in the stabilized case, the response terms, $(\Delta\text{Long})_r + (\Delta\text{Short})_r$, are negligible. This is physically reasonable, because in the geoengineering case, those aspects of climate system that would affect radiative transfer, such as temperature and water vapour, do not differ substantially from the control climate. This leads Bala et al. to the conclusion that changes to the radiative forcing—which are negative because F is primarily the solar forcing, which is being reduced—must be balanced by changes (i.e. corresponding decreases)to ΔLatent and ΔSensible:

$$F \approx \Delta\text{Latent} + \Delta\text{Sensible}$$ **Equation 1.10**

As Bala et al. note, this is complementary to an analysis of the atmospheric heat budget, such as the one done by Allen and Ingram, (2002).

Allen and Ingram found that the precipitation response to changes in temperature did not depend simply on the availability of moisture, as one might expect from looking at what is implied by the Clausius-Clapyron[2] equation alone. Rather, the strength of the hydrological cycle seems to also depend on the ability of the troposphere to radiate away latent heat: as moisture condenses before precipitating out of the atmosphere, it radiates away latent heat in order to do so. Should the troposphere's ability to radiate away latent heat be compromised, as happens from a buildup of anthropogenic greenhouse gases, then this will weaken the hydrological cycle. Allen and Ingram demonstrate this as follows. First, following Mitchell et al., 1987, they present the following approximation of the perturbation energy budget of the troposphere:

$$\Delta\text{Cooling}_I + \Delta\text{Cooling}_D = \Delta\text{Latent}$$ **Equation 1.11**

where: $\Delta\text{Cooling}_I$ is the component of the perturbation radiative cooling that is independent of the temperature change because it is due purely to external drivers of climate change (such as atmospheric greenhouse gas concentrations); $\Delta\text{Cooling}_D$ is the component of the perturbation radiative cooling that is dependent upon temperature, i.e. $\Delta\text{Cooling}_D = k\Delta T$, where ΔT is the temperature change and $k = 3\ \text{Wm}^{-2}\text{K}^{-1}$; and ΔLatent is the perturbed latent heating, which is comprised of the latent heat of evaporation (L)multiplied by changes in global mean precipitation, ΔPrecipitation,

$$L \times \Delta\text{Precipitation} = \Delta\text{Latent}$$ **Equation 1.12**

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[2] The Clausius Clapyron equation relates saturation vapour pressure to temperature: $\frac{d\ln e_s}{dT} = \frac{L}{RT^2}$ where e_s is the saturation vapour pressure, R is the ideal gas constant, T is temperature and L is the latent heat of evaporation.

So,

$$\Delta Cooling_I + \Delta Cooling_D = L \times \Delta Precipitation$$ **Equation 1.13**

Allen and Ingram (2002) consider a doubling of atmospheric concentrations of CO_2 which decreases the amount of outgoing longwave radiation flux at the top of the troposphere by roughly 3 Wm^{-2}-4 Wm^{-2} and increases the infrared flux at the surface by roughly 1Wm^{-2}, hence resulting in $\Delta Cooling_I \approx$ -3 $Wm^{-2}$to -4 Wm^{-2}. If the tropospheric temperature doesn't change significantly (e.g. if there is a simultaneous decrease in incoming solar radiation due to increased stratospheric aerosol load from a volcanic eruption) and $\Delta Cooling_I$ decreases, then, they argue, ΔPrecipitation must also decrease. Applying this result to the GeoMIP experiment, a reduction in precipitation is expected, because the warming due to the increase in atmospheric greenhouse gas concentrations is being offset by a decreased solar constant.

Another potential issue with stratospheric aerosol geoengineering is that it requires constant maintenance in order to be effective. Should the geoengineering maintenance be disrupted for a significant period of time (on the order of the residence time of stratospheric aerosols, roughly a year) for any reason—e.g. global political or economic instability, or as a reaction to unseen negative consequences of this form of geoengineering—the ensuing failure could be quite severe. Matthews and Caldeira (2007) found a warming rate of around 20 times our (already rapid) modern warming rate, though their experiment used a solar constant reduction and not aerosols. A similar rapid warming rate upon termination of geoengineering was found in an aerosol geoengineering experiment by Robock et al. (2008) with a consequent decline in, sea ice area.

There are, no doubt, many other issues which need to be addressed before stratospheric sulfate aerosol geoengineering could be considered even remotely viable. A partial list of these issues includes potential effects on solar energy production, increased acid rain and its consequent effects on ecosystems, as well as the effect of sulfate aerosol geoengineering on plant photosynthesis, due to decreased sunlight (Robock, 2008). These are all to be considered in addition to the basic ethical questions that will be touched upon in the ethics section.

1.8 The Geoengineering Model Intercomparison Project

Given the above concerns about anthropogenic climate change and the potential effectiveness of stratospheric sulfate aerosols at reducing global temperature at a relatively low cost, this form of geoengineering might seem attractive to policy makers as a complement to emissions reductions.

However, we have also seen that there are myriad potential impacts, from ozone depletion and a potential weakening of the hydrological cycle to acid rain; moreover, should geoengineering be shut down for whatever reason, the ensuing climate response will likely be abrupt and severe. In light of these factors, a robust body of scientific knowledge (along with contributions from other fields, including ethics, politics, economics, etc.) is needed to inform public policy discourse, so that all of the facts can be on the table for the decision making process.

Though there has been a number of experiments carried out on stratospheric sulfate aerosol geoengineering, results cannot be directly compared for a variety of reasons, ranging from the emissions scenarios used, to the amount and location of the sulfate injections (Kravitz et al., 2010). Also, the full extent to which results obtained thus far are model dependent is not completely understood (Kravitz et al., 2010). Hence the need for a set of standardized experiments to be carried out across a large number of models, so that the results can be compared and the potential response of the climate system better understood. A detailed discussion of the setup for the GeoMIP experiments is in the methodology section (Section 2) of this thesis.

1.9 Ethical Considerations

A full treatment of the ethical questions posed by geoengineering is beyond the scope of this thesis. However, given the profound ethical questions which geoengineering raises, a short discussion of the primary arguments for and against a research program into stratospheric sulfate aerosol geoengineering is warranted and will be presented here.

The ethical issues surrounding geoengineering—and climate ethics more generally—are embedded within the field of environmental philosophy. Environmental philosophy poses large questions that range in their nature from metaphysics to ethics and metaethics. Among these questions and especially relevant to geoengineering proposals, environmental philosophy raises questions about which subjects—human, non-human, present and future, etc.—or systems are morally valuable and, of those morally valuable subjects and communities of subjects, questions about what considerations of justice, rights and other moral obligations arise.

Two selections from the literature addressing the ethics of stratospheric sulfate aerosol geoengineering will be discussed here. These articles were chosen because they directly address the ethics of the limited modelling research of which this thesis is a part and because they outline the primary issues with stratospheric sulfate aerosol geoengineering more generally. Because

GeoMIP is meant to evaluate the climate effects of this form of geoengineering, the following section provides an ethical context in which the results of this thesis can be considered. It will also be argued below that the arguments supporting the objections against the form of limited modelling research of which this thesis is a part are not sound.

It should be noted that, while this thesis does address the main concerns for limited modelling studies, the range of ethical issues opened up by sulfate aerosol geoengineering is so wide that only a partial discussion of these broader ethical issues is possible here. Though this serves to provide context, it must be stated that, even if the issues for sulfate aerosol geoengineering presented here were to be addressed, more would remain.

1.9.1 ALAN ROBOCK'S OBJECTIONS TO GEOENGINEERING DEPLOYMENT

Writing in the Bulletin for the Atomic Scientists, Alan Robock (2008) presented 20 objections to stratospheric sulfate aerosol geoengineering. The ethical objections will be discussed in brief, here.

Robock's first objection is that it is not clear that humans have the moral authority to affect the ecosphere by geoengineering. (This question, on its own, would take a large field of research to explore.) The response would clearly be determined by the ethical system being used. For instance, whereas a Kantian deontologist could begin by looking at the way geoengineering could affect the autonomy of the human beings involved and what each person would assent to as being a universal law and the moral rules and duties which would be entailed (Sterba et al.,1999, 171-185), a deontologist who follows Tom Regan's (1983) view that subjects of a life (including animals) are morally valuable and have the right not to be harmed, would bring different considerations on which actions, rules and duties come into play. A consequentialist would examine not the actions themselves, but rather, their outcomes and how these outcomes affect the well-being of all the morally considerable beings (not necessarily simply human beings). The arguments can only get more subtle and complicated from there, depending on one's overall environmental philosophy. For example, an ecofeminist could ask if geoengineering counts as further patriarchal violence and domination of nature, causing whole ecosystems to now be dependent on technology, in a move that reflects an earlier colonial mindset; a deep ecologist could ask not only what harms this could effect on ecosystems, but also if geoengineering helps to feed broader metanarratives whereby people fail to see their interconnectedness with natural systems (termed "their ecological selves").

Two general remarks can be made however. First, arguments for human moral authority will be more easily defensible ethically to the extent that they reflect the broad interests of the moral agents who will be impacted by geoengineering deployment. Second, human moral authority over the ecosphere will be significantly more difficult to justify—albeit, not necessarily undermined completely—if geoengineering must be performed as a result of human moral failure. (Though asking for a flawless moral authority is unrealistic, ideally, moral authorities are not prone to catastrophic lapses in moral judgment.)

Robock argues that there might well be military applications of geoengineering and that such weaponization or adverse regional climate effects would violate the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD). This is a serious objection to any programs that would deploy geoengineering and touches upon the geopolitical dimensions inherent in manipulation of the Earth's climate. While this too is a broader question than can be addressed in this thesis, it is worth remarking that this objection only applies to geoengineering that is deployed. The sort of basic modeling research done in GeoMIP is not morally problematic in this way. Further, it should be noted that this matter is worth pursuing even if stratospheric sulfate aerosol geoengineering is not deployed, because other, ostensibly more benign forms of geoengineering, such as large-scale reforestation and carbon scrubbing projects could also count as environmental modification techniques that effect regional climate.

Another objection raised by Robock is that it isn't clear who gets to decide what the Earth's climate should be. This again touches on much larger geopolitical questions which are beyond the scope of this thesis. Further, given that countries can still not agree on basic issues of social justice and land claims (e.g. who has what territory in the Arctic), it is questionable if international agreement on the Earth's climate will be possible at all, much less in line with norms of international justice. The potential for individual nations to unilaterally applying geoengineering only compounds the problem.

In his paper, Robock raises the challenge that geoengineering might undermine emissions reduction efforts. As discussed below, this is clearly a valid objection that must be weighed against any potential benefit from geoengineering. To ignore emissions reduction efforts and rely on geoengineering alone to solve climate change is akin to taking up smoking and counting on a heart bypass to deal with any potential future heart disease. Anyone who were to brush off the dangers of smoking with the idea in mind that she or he would simply go in for a heart bypass surgery would be making an obviously short-sighted and potentially catastrophic decision.

Similarly, to rely on indefinite sustained stratospheric sulfate aerosol geoengineering for the short term benefits of continuing along a business as usual emissions trajectory with regard to fossil fuels is an obviously short-sighted and potentially catastrophic decision. Geoengineering would then need to be pursued indefinitely, as carbon dioxide levels would continue to rise and, as will be seen in Chapter 4 of this thesis, should geoengineering be terminated abruptly for any reason, the consequent rates of climate change could potentially be very large.

Robock also argues for further research so that we can know whether or not geoengineering is a bad idea and, if so, how bad and for what reasons. Though this may seem simple, it is in fact, a complicated claim that leads into Stephen Gardiner's objections to geoengineering research, below.

This section has provided a part of the ethical context within which the research in this thesis is being conducted, but several important points remain, including, but not limited to, an analysis of "lesser evil" ethical arguments offered as justification for geoengineering research, an analysis of cost-effectiveness arguments and an analysis of arguments which call for limited research first. These will now be addressed.

1.9.2 STEPHEN GARDINER'S OBJECTIONS TO GEOENGINEERING RESEARCH

In his 2010 paper, *Is "Arming the Future" with Geoengineering Really the Lesser Evil? Some Doubts about the Ethics of Intentionally Manipulating the Climate System*, Stephen Gardiner challenges several arguments for stratospheric sulfate aerosol geoengineering research (to which he restricts his attention). He begins with what he terms the "Cost-Effectiveness Argument" and the "Research First Argument," before moving on to the argument that he sees as most likely to motivate stratospheric sulfate aerosol geoengineering research and deployment, which he terms the "Arm the Future Argument" (AFA).

Both the "Cost-Effectiveness Argument" and the "Research First Argument" are worth considering here: the first, because it draws out the costs of side effects, a debate which the GeoMIP project will help to inform; the second, because it argues directly against the undertaking of research into geoengineering, including projects such as this thesis.

The Cost-Effectiveness Argument suggests that stratospheric sulfate aerosol geoengineering should be pursued because it is "orders of magnitude less expensive than switching whole economies to alternative energy [and] [i]t is said to be administratively simple because action need not require international agreement" (Gardiner, 2010). To this Gardiner raises four objections: (1) that this particular form of geoengineering only addresses part of the problem, ignoring other issues, such as ocean acidification; (2) the costs presented are those for getting sulfate aerosols into the stratosphere, but ignores the costs of side effects; (3) the argument assumes an administrative simplicity that appears “morally and politically naïve” (Gardiner, 2010); (4) the argument encourages a shallow and perhaps dangerous view of the relationship between humans and nature—specifically, adopting a geoengineering solution might encourage more potentially hazardous interventions in the future and further domination of nature.

The first three of these objections are sound. Stratospheric sulfate aerosol geoengineering is not intended to and will not prevent increasing ocean acidification from rising atmospheric carbon dioxide concentrations. The costs of the side effects are still unknown and the costs from a potential collapse of geoengineering and the sudden shift in global climate are potentially quite large. Given the geopolitical climate, it is difficult to believe that global agreement on geoengineering will be reached without the expenditure of considerable capital, both economic and political and, further, it is difficult to believe that there would not be political consequences should one nation decide, unilaterally, to alter the planet’s climate system. However, the fourth rebuttal is problematic, in that just what is meant by the “domination of nature” is not explained. The sort of compassionate interventions envisioned by Oscar Horta (2010)—whereby we have a moral duty to interfere in nature, not only for human well being and environmental reasons, but also when we can reduce the harms that wild animals suffer—could be seen as “domination,” but would entail an entirely different set of ethical arguments than those that surround mining, hunting and logging, which would each require separate ethical considerations again. If what Gardiner means is that the issue rests upon the commodification of nature, then there is much to be done with his argument to demonstrate that geoengineering will encourage this sort of view, instead of, perhaps one of attempting to protect the ecosystems and inhabitants of the Earth from further harm. Also, Gardiner does not give an argument for why pursuing geoengineering will encourage other potentially hazardous interventions in the future. Despite the problems with this last objection, the first three objections, whether taken separately or together, present an effective challenge to the “Cost-Effectiveness Argument,” at least taken in its present form.

The “Research First Argument” argues that research into geoengineering should be separated into research that does not involve field testing and research that does involve field testing or deployment. The Research First Argument states that the former should be pursued to separate good proposals from bad proposals and that the knowledge gained from this basic research could be worthwhile for its own sake. This will be dealt with in some detail because it is, in part an argument against precisely the sort of research being done in this thesis and if it holds, the unethical nature of even limited modelling research, such as the basis for this thesis, would be established.

Gardiner raises the following objections: (1) the knowledge to be gained from geoengineering is insufficient to justify funding it, given that such funding displaces funding for other projects that would be of greater benefit; (2) geoengineering research at present might turn out to be trivial because, given the timescale involved and the rate of technological progress, it makes little sense to do this research now; (3) the potential for gaining knowledge doesn't justify research into a morally bad project, such as geoengineering; (4) due to "institutional momentum," whereby "big projects that are started tend to get done," (Gardiner, 2010) and owing to the open source nature of the research into geoengineering, it isn't clear that geoengineering will be limited merely to research.

Each of these objections is problematic. Addressing the first and third objections together, it isn't altogether clear that the knowledge to be gained from modeling studies for geoengineering is insufficient to justify such research, nor is it clear that the modeling research into potential geoengineering outcomes is bad in and of itself. In order to see why this is so, first consider the possible outcomes of such research. One outcome is that the research does demonstrate that stratospheric sulfate aerosol geoengineering is a "good" proposal, offsetting great harm at a minimal cost, with insignificant side effects. In that case, arguments from the lesser evil would not apply and the research would be of obvious use in combating the worst effects of anthropogenic climate change. Another outcome is that this geoengineering proposal is simply not good for any number of reasons. In this case, the research will demonstrate that fact and accordingly make it less likely that geoengineering will be pursued for political ends[3] though scientific research can at best only inform policy and not dictate it. Gardiner notes this potential response in a footnote and questions if the research "will be enough to circumvent the political forces in favour of geoengineering" and counters: "is it worth 'wasting' scant scientific resources in this effort?" (Gardiner, 2010.) Again, the place of scientific research in climate science as it affects policy is not to "circumvent political forces," but rather to inform policy discussions. Insofar as the body of research on stratospheric sulfate aerosol geoengineering demonstrates that

[3] Admittedly, situations can occur in which a hermetically-sealed political discourse arises which is entirely disconnected from scientific input, as has occurred with Lysenkoism in the Soviet Union (Wrinch, 1951) and as is occurring with regard to several branches of environmental science under the Harper Government in Canada, presently (Anonymous, 2012; O'Hara, 2010). Perhaps, in the final analysis, there is simply no accounting for the idealogically motivated ignoring of scientific results.

it is a hazardous idea, it will make such geoengineering proposals less likely to be pursued. As to whether or not such basic research is worthwhile, a reasonable argument could be made that, insofar as one values developing a further understanding of the Earth's climate system under perturbations from the current climate and outlining the potential dangers of geoengineering, the research is worthwhile.

Though arguments have been offered above to answer Gardiner's challenge as to whether there is any value in the sorts of geoengineering research done in GeoMIP, one might further question the method of argument which Gardiner employed, in which different forms of research are compared solely by the metric of usefulness. Many areas of research are funded without obvious immediate usefulness for society, aside from the acquisition of knowledge—from modeling the evolution of distant galaxies and the climates of other planets to studying neutrinos and algebraic number theory. It is not entirely clear that it is reasonable to argue that funding should simply be cut for those areas that are not obviously immediately useful, such as particle physics, stellar astrophysics and pure mathematics, so that greater funding can be given to areas that are more obviously useful. It is also unclear to whom the usefulness must be obvious. Moreover, it is often difficult to assess ahead of time the full value that the findings of such basic research will have, which makes such a metric hard to apply. If Gardiner wishes to apply such a metric here, further argumentation is required.

Regarding the second argument, it is true that the price-performance of computers is quickly growing and hence, assuming that these trends continue to hold, any computationally intensive research will be easier, cheaper and take less time for generations in the foreseeable future than at present. However, the fact that future computers will have greater price-performance than today's computers is not a good reason to delay research for several reasons. First, there is more to research than simple computation; developing an understanding of a problem that is both qualitative and quantitative takes time—and deciding where to go from there once one has such an understanding can also be time consuming. Second, when decisions regarding the well-being of future generations are at stake, it is potentially dangerous to put off research into solutions to global problems under the assumption that the research will be trivial with future technologies, because those technologies might not be as powerful as hoped and hence, valuable time for research could be wasted. Third, since computers were first invented, it has been the case that computationally intensive research has become easier and easier. However, putting off research on those grounds alone amounts to putting off research indefinitely, until that future date when computer price-performance is no longer increasing at a rapid rate. Fourth, it is possible, though presumably unlikely, that an unforeseen climate emergency of some sort requiring geoengineering will happen in the relatively near future and hence, putting off research will leave society unable to confront such a catastrophe or scrambling with geoengineering technology for which potential side effects have not been explored.

Regarding the fourth objection, large projects get cancelled all the time. NASA's Constellation Project, set to return Americans to the moon was canceled after a nine billion dollar investment. Moreover, even if it is possible that a clumsy set-up could create institutions which promote geoengineering, this is not an argument against geoengineering per se, but rather, an argument for the careful creation of any institutions dealing with geoengineering. This could take many forms, such as an institutional mandate to always put mitigation first, or by putting geoengineering decisions in the hands of an organization whose existence does not depend on or benefit from geoengineering, such as the United Nations. (None of this is to say that actual geoengineering deployment is not fraught with political problems—because it is—but, simply, the issue of institutional momentum is not an argument against geoengineering itself. Also, larger political problems concerning the geopolitics of determining the Earth's climate and the potential weaponisation of geoengineering seem to present greater problems for geoengineering deployment.) At any rate, there is a difference in scale between such large, institution-generating proposals and the modeling research conducted as part of GeoMIP, so this objection likely does not apply to this thesis.

Hence, by the analysis of Gardiner's four objections above, his rebuttals to the Research First argument are not sound and hence, he fails to establish that limited modelling research into geoengineering is unethical.

After presenting these arguments, Gardiner moves on to the AFA., In short, the AFA is a form of "lesser evil" argument that begins by conceding that emissions reduction is the best solution to anthropogenic climate change and that stratospheric sulfate aerosol geoengineering is morally problematic (Gardiner, 2010). The argument moves forward by noting that there has been political inertia for emissions reduction approaches and that, if this continues, future generations may well be faced with the choice between catastrophic changes to climate or deploying geoengineering technology. Though both are bad, geoengineering is the lesser evil. AFA concludes that geoengineering technology will not be available for future generations unless research into geoengineering begins in the present. Hence, the argument suggests that it is imperative that the current generation "Arm the Future" generations with the relevant geoengineering research such that they can avoid catastrophic climate change.

He presents the argument formally, as paraphrased below (P's denote premises and C's denote the conclusions drawn from the preceding premises):

P1: Emissions reduction is the best way to deal with anthropogenic climate change.

P2: In the past 15 years there has been insufficient progress on emissions reduction.

P3: It is likely that there will not be sufficient progress on emissions reduction in the near future.

P4: If sufficient progress on emissions reduction is not made soon, present or future generations might end up faced with the option of either allowing catastrophic climate change to occur or deploying geoengineering.

P5: Both of these are "evils," or bad options.

P6: Geoengineering is the lesser of the two evils.

C1: Therefore, should present or future generations be forced to choose between these two bad options, the appropriate choice should be the lesser evil, namely, geoengineering.

P7: If the present generation does not undertake serious geoengineering research soon, it will not be available as an option in the future.

C2: Therefore, the present generation should begin geoengineering research now.

To this, Gardiner raises a number of objections: (1) the likelihood of climate catastrophes isn't well-understood; (2) the "two evils" might not be the only alternatives; (3) given that any sort of climate catastrophe is not upon the present generation, there may be better ways to prepare or more owed to future generations than geoengineering; (4) geoengineering research could create political inertia, reducing the likelihood of mitigation; (5) unless the root cause of the political inertia surrounding climate change can be addressed, geoengineering solutions will face similar resistance to mitigation efforts.

Regarding the first objection, it is true that the likelihood of catastrophic climate change isn't well constrained, however Gardiner does not provide a precise definition of what qualifies as "catastrophic." For instance, there is research that suggests that changes to the global temperature of roughly 3-4 °C above preindustrial temperatures will be sufficient to cause a dieback of boreal forests and the Amazon rain forest (Lenton et al., 2008). While these are the results from one model and highly model-dependent, they raise the possibility of effects that could be termed "catastrophic." Similarly, significant changes to the West African Monsoon, Indian Summer Monsoon, Greenland Ice Sheet and West Antarctica Ice Sheet as a result of anthropogenic climate change could bring about serious impacts to human systems and ecosystems, which could plausibly be called catastrophic (for more details about the impacts of severe climate change, see Parry et al., 2007). Allison et al. (2009) state that, "1 °C global warming (above 1980-1999) carries moderately significant risks of passing large scale tipping points[4], and 3 °C global warming would give substantial or severe risks." At this point it seems that, under plausible emissions trajectories, future generations could face such impacts and hence, what could reasonably be termed catastrophic climate change. Hence, it seems likely that interest in geoengineering will likely only increase and hence, research into its potential benefits and pitfalls appears justified.

The second objection points out that there might be more than the two evils which are on offer. This is a valid objection because, even assuming that emissions reduction efforts fail, there are certainly other geoengineering options and adaptation measures to be considered, which might well provide greater benefits with fewer risks than stratospheric sulfate aerosol geoengineering. It is important to note that this isn't an argument against modeling studies such as GeoMIP, which will help us assess the benefits and risks of this method of geoengineering , though it might well be an argument against field testing and further deployment.

Gardiner's third objection, that there may be better ways to prepare for potential climate catastrophes than stratospheric sulfate aerosol geoengineering, or that more might be owed to future generations than geoengineering, is a strong one. Assuming that present generations have moral duties to future generations[5] and, given that future generations might be facing costly impacts from severe climate change, it follows that, as Gardiner suggests, present generations have an obligation to compensate them for this damage. It also follows that, should emissions reduction legislation not be forthcoming, present generations would have an obligation to do whatever is possible to indirectly limit emissions, such as through the funding of clean energy. However, again, this argument does not affect modeling the results of stratospheric sulfate aerosol geoengineering, which would be a part of evaluating which approaches have better (or worse) results, in a qualitative manner.

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[4] A "tipping point" is, "a critical threshold at which the future state of a system can be qualitatively altered by a small change in forcing." (Allison et al., 2009.)

[5] The extent of the moral duties that the present generation owes to future generations is itself a complicated issue and the interested reader is directed to Brennan and Lo (2010) for a description of the arguments and issues surrounding such duties or the lack thereof.

Regarding the fourth objection, it is clearly a valid concern that geoengineering has the potential to create political inertia regarding emissions reduction. For the proponent of geoengineering, this must be weighed against the benefits of the approach. However, again, this is not an argument against modeling assessments of the methods. First, any potential dangers that the modeling assessments demonstrate will surely count against geoengineering deployment. Second, were the modeling assessments to show that geoengineering were to prevent great harm at minimal cost and with few side effects, then Gardiner's objection would hinge on a proper cost-benefit analysis of the approach versus the harms of its attendant effect on political inertia surrounding mitigation being performed.

Gardiner's fifth objection is valid, but perhaps only to a limited degree. There are several "root causes" of the political inertia surrounding emissions reduction. First, as discussed above, there is pressure from industries whose profits would be affected by emissions reduction legislation. Second, developing nations whose standard of living would improve due to the utilization of their fossil fuel resources have, ostensibly, an interest in preventing legislation which would limit their emissions. Third, there is the issue of global justice, the question of who will pay for emissions reductions. (It could be argued that developed economies should shoulder more of the burden, given that they are responsible for the largest portion of current elevated atmospheric greenhouse concentrations). These are three of the more important sources of political inertia on emissions reduction. On the face of it, what has motivated the first two groups to oppose emissions reduction efforts will not motivate them to oppose geoengineering. However, regarding the third source, it is quite possible that global justice concerns will arise in the arena of geoengineering, both in terms of who will pay for it and in terms of global-justice motivated grassroots opposition to geoengineering. So it is plausible that geoengineering will face some, but not all, of the same resistance that mitigation efforts have, and not from all of those who have opposed emissions reductions.

To summarize, Gardiner raises a number of strong objections to the field testing and deployment of stratospheric geoengineering. However, for the reasons above, Gardiner's objections to the Cost-Effectiveness Argument, Research First Argument and AFA do not, upon examination, hold against limited modelling studies such as GeoMIP, with which this thesis is concerned. Hence, the objection that such research efforts are unethical has not been demonstrated.

However, it should be further noted that Robock et al. (2010) argue that full-scale implementation would be necessary to properly test geoengineering. Whether such testing proceeds may depend, in part, on earlier modeling studies, such as GeoMIP. If it is the case that full stratospheric sulfate aerosol geoengineering deployment is necessary for testing, then much further argument must be provided to Gardiner's objections than what has been given here, in order to determine under what conditions (if any) such full-scale testing can be ethically defensible.

2 Methodology

2.1 Methods

2.1.1 MODEL USED

The model used for these experiments was the Canadian Centre for Climate Modelling and Analysis's CanESM2 climate model. All of the model output used for this thesis was taken from this model. All runs were conducted by CCCma staff as contributions to GeoMIP and the Coupled Model Intercomparison Project Phase 5, in support of the upcoming Fifth Assessment Report of the IPCC. For full details on the model, see the Canadian Centre for Climate Modelling and Analysis: Model Specifications (2010), further details can also be found in Aroroa et al. (2011) and Chylek et al, (2011), the references therein and in the papers cited for each section of the model, below. CanESM2 model consists of the CGCM4 general circulation model, the Canadian Terrestrial Ecosystem Model (CTEM) for terrestrial carbon cycling (Christiansen et al., 2010) and the Canadian Model of Ocean Carbon (Zahariev et al., 2008). The CGCM4 itself consists of two components: the AGCM4 atmospheric component (Scinocca et al., 2008) of resolution 2.81° by 2.81°, and 35 vertical layers and an OGCM4 ocean component, of resolution 0.94° latitude by 1.4° longitude, with 40 vertical levels that vary in height from 10m near the surface, to almost 400m in the deep ocean. Hence, there are 6 ocean cells beneath each atmospheric cell. The model is also coupled to a sea ice model. The ocean model component of CanESM2 was developed from the National Center for Atmospheric Research's Climate System Model Ocean Model (NCOM). Hence, Gent 1998 and Gent 1995 describe the basic model and parameterization of the isoneutral mixing, respectively; Large et al. (1994) describes the model's vertical mixing; McDougall et al. (2003) describes the equation of state for sea water; the amount of insolation that is photosynthetically active follows Baker and Frouin (1987) and the penetration of light into the ocean follows Lima and Doney (2004). For more information, see the Canadian Centre for Climate Modelling and Analysis: Model Specifications (2010).

It should also be noted here that the sea ice model has a recognized low bias in terms of sea ice thickness (Maslowski et al., 2012) which could potentially present an issue for the sea ice results here.

2.1.2 MODEL EVALUATION

There is a rather large body of material addressing various parts of the CanESM2. A paper detailing the atmospheric portion of the model and including a comparison of model results versus observations for various climatologies is forthcoming (von Salzen et al., 2012). In addition to the peer reviewed papers that contain documentation of the model, this version of the CanESM has undergone considerable testing and validations against observational data by the CCCma as part of the model's development. In light of this, we can proceed with some confidence in the model's ability to represent both equilibrium and perturbed states of the climate system.

2.1.3 GEOMIP EXPERIMENTAL SETUP AND ADDITIONAL MODEL RUNS

The Geoengineering Model Intercomparison Project (GeoMIP) consists of a set of four standardized experiments termed G1 to G4, run by a large number of models from a variety of research institutions[6] to further explore the potential promise and shortcomings of shortwave radiation management geoengineering in general and stratospheric sulfate aerosol geoengineering in particular.

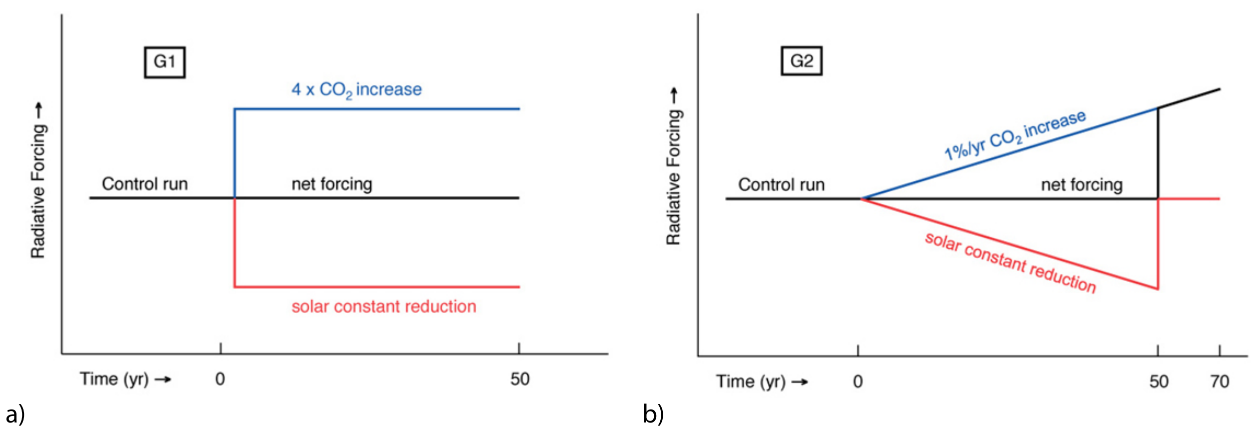

Figure 2.1: GeoMIP Experiment Schematics
Schematics for GeoMIP experiments: a) G1, b) G2
From (Kravitz et al., 2010).

The first two GeoMIP experiments begin from a long, suitably equilibrated control simulation, in which all external climate forcings are held constant at pre-industrial levels. In the G1

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[6]Participating institutions: Max Planck Institute for Meteorology, Laboratoire des Sciences du Climat et de l'Environnement, NASA Godard Institute for Space Sciences, Rutgers University, Norwegian Climate Centre, Pacific Northwest National Laboratory (US Department of Energy), National Center for Atmospheric Research, Hadley Centre, Max Planck Institute for Chemistry, University of Bristol, Cambridge University Institute for Atmospheric Physics (Russian Academy of Science), Beijing Normal University, Commonwealth Scientific and Industrial Research Organisation, Canadian Centre for Climate Modelling and Analysis, Centro Euro Mediterraneo per I Cambiamenti Climatici and the Danish Meteorological Institute.

experiment (Kravitz et al., 2011a; Kravitz et al., 2011b), the atmospheric carbon dioxide concentration is instantaneously quadrupled from preindustrial levels and the solar constant is reduced to offset the forcing (Figure 2.1a). The first part of the experiment lasted for 50 model years, at which time geoengineering ceased abruptly and the model was allowed to run for an additional 50 model years, allowing for an examination of the effects of the termination of geoengineering.

In the G2 experiment (Figure 2.1b), the atmospheric carbon dioxide concentration was increased by 1% per year, for 50 years and the solar constant was reduced in concert with the increasing carbon dioxide, to offset the forcing of the latter, by the same criterion mentioned above for G1. After 50 years, geoengineering was terminated, as in G1, in order to study the effects of the termination of geoengineering.

In practice, the attainment of a balanced state is an iterative process, because the amount of solar constant reduction necessary to offset the $4 \times CO_2$ forcing is unknown a priori. The (primarily longwave) $4 \times CO_2$ forcing is of magnitude 7.8 Wm^{-2} in CanESM2 . It was found that to offset this required a reduction in the solar constant is 4.0 % (55 Wm^{-2})—which corresponds to a reduction in net shortwave radiative flux at the top of the atmosphere of 7.8 Wm^{-2}. This produced an atmospheric net radiative flux difference of less than ± 0.1 Wm^{-2} from the control value, the threshold mandated by the GeoMIP guidelines for the G1 and G2 experiments.

There are two further experiments that are a part of GeoMIP, though the results of these will not be a part of this thesis. In the G3 experiment, the forcing is specified using the Representative Concentration Pathway 4.5 (RCP4.5) scenario (Moss et al., 2008), in which the radiative forcing increases to a value of approximately 4.5 Wm^{-2} by the year 2100. This RCP4.5 forcing is offset, starting in the model's year 2020 (to allow for enough time for development of the requisite delivery technologies for injecting sulfate aerosols into the stratosphere) by an injection of sulfate aerosols into the atmosphere. The G4 experiment involves specifying the forcing using the RCP4.5 scenario, but this time, starting in the model's year 2020 and continuing on until the model's year 2070, there will be a fixed injection of 5 Tg per year of SO_2 into the lower atmosphere (an altitude of ~16-25 km) from the Equator.

In addition, two further model runs were completed, one in which the atmospheric carbon dioxide concentration was instantaneously quadrupled from a pre-industrial control run and one in which the atmospheric greenhouse gas concentration was slowly increased, at the rate of 1%

per year from a pre-industrial control run, for 50 years. These runs were used for comparison to G1 and G2, respectively.

2.1.4 ANALYSIS OF MODEL OUTPUT

Geoengineering proposals that work by altering the Earth's radiative balance might be expected to affect a number of climatic variables aside from surface air temperature: precipitation (Blackstock, J.J., et al., 2009; Shepard, J. et al. 2009)—in both spatial patterns and in the overall global mean—sea ice volume, ocean heat content and the strength of the Atlantic Meridional Overturning Circulation (AMOC), among many others. Upon the termination of geoengineering, for whatever reason, these variables could respond rapidly and the details of these changes are of some interest. Hence, this study examines each of these variables as follows.

For the G1 and G2 experiments, two dimensional surface temperature and precipitation anomalies were created for the December, January, February and March Period (DJFM), the June, July, August and September period (JJAS), as well as the annual period. In order to do this, ensemble means were made from three runs each for the G1 and G2 experiments and an "ensemble" average was created from three forty-year periods from a pre-industrial control run. The model runs were then separated into two periods: geoengineering (the first 50 years of the run) and post-geoengineering (the last 50 years of the run). The ensemble averages were each truncated, such that the first 10 years of each period were removed owing to the model's initial adjustment to the large forcing in G1 over the first 10 years. Following this, anomalies were generated by taking the difference of the experimental ensembles and the control ensemble for each experiment and for both the geoengineering and post-geoengineering periods. Two-dimensional longitude-latitude means were then obtained by averaging over time and the spatial structure of the resulting data was then plotted and examined. A Student's t-test was then performed to determine over which areas the changes were statistically significant at the 95% confidence level.

In addition, time series anomaly plots of global means of surface temperature, precipitation and ocean temperature (here being the average temperature of the entire 3D ocean, not merely the surface temperature) were made from the runtime diagnostics (RTD) files. Plots of the strength of the Atlantic Meridional Overturning Circulation (AMO), Northern Hemisphere summer sea ice volume and Southern Hemisphere summer sea ice volume were also made from the RTDs. These time series plots were made for the G1 and G2 experiment, as well as the corresponding 4 $\times$ CO_2 run and 1%yr^{-1} CO2 run. For the 4$\times$ CO_2 run and 1%yr^{-1} CO2 run, only one run each were available. All anomalies were relative to the same "ensemble" of the mean of three periods from the control run (the same three periods as for the longitude-latitude plots above).

The rates of change for global surface temperature, average ocean temperature, Northern Hemisphere (NH) and Southern Hemisphere (SH) sea ice volume as well as Atlantic Meridional Overturning Circulation (AMOC) were determined for G1 and G2 experiments in the decade following geoengineering and for the first decade of the $4 \times CO_2$ and 1% increase of CO_2 yr^{-1} experiments, for comparison.

3 Results from the Geoengineering Period

3.1 Temperature Changes: G1 versus Preindustrial Control

3.1.1 G1 ANNUAL MEAN GLOBAL AND ZONAL TEMPERATURE RESULTS

Though there is negligible warming overall in the G1 experiment (Figure 3.1), by experimental design, there is a zonal structure, with a pronounced warming in the high latitudes and polar regions being offset by cooling in the tropics (Figure 3.2). The zonal temperature anomaly for the $4 \times CO_2$ climate is shown in Figure 3.3, for comparison.

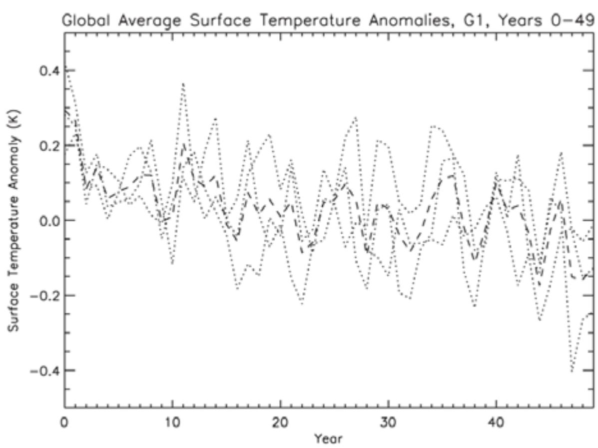

Figure 3.1: G1 Global Average Surface Temperature Anomalies
Ensemble mean (thick dashed line) and individual ensemble members (thin dotted lines).

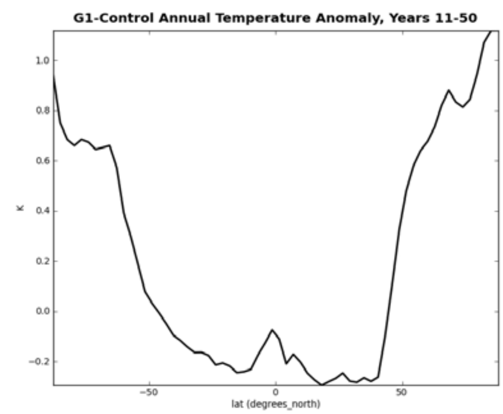

Figure 3.2: G1 Temperature Anomaly by Latitude
Temperature anomaly by latitude [K] G1-Control, years 11-50.

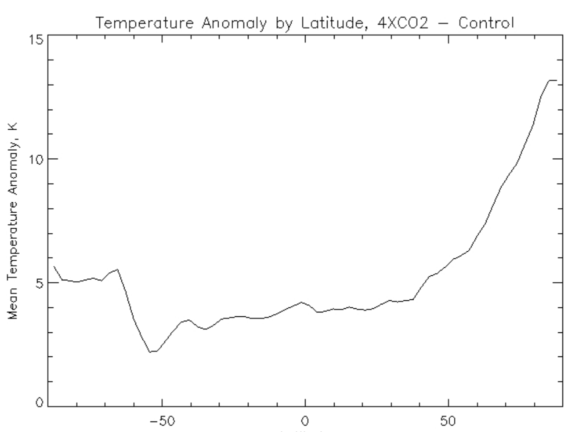

Figure 3.3: $4 \times CO_2$ Temperature Anomaly by Latitude

Govindasamy and Caldeira (2003) show the seasonal structure of the radiative forcing from a 4 × CO_2 experiment (Figure 3.4, upper) and the necessary decrease in insolation sufficient to offset the radiative forcing from the increased CO_2 (Figure 3.4, lower). The strong seasonality of the solar forcing is evident from Figure 3.4 (lower), with insolation contributing strongly over the summer hemisphere and much less to the winter hemisphere. In the G1 experiment, the overall forcing, which can be seen in Figure 3.5, is the sum of these forcings—the solar reduction with its strong seasonal variation and the smoother 4 × CO_2 forcing. In CanESM2, this 4 × CO_2 forcing is 7.8 Wm^{-2}.

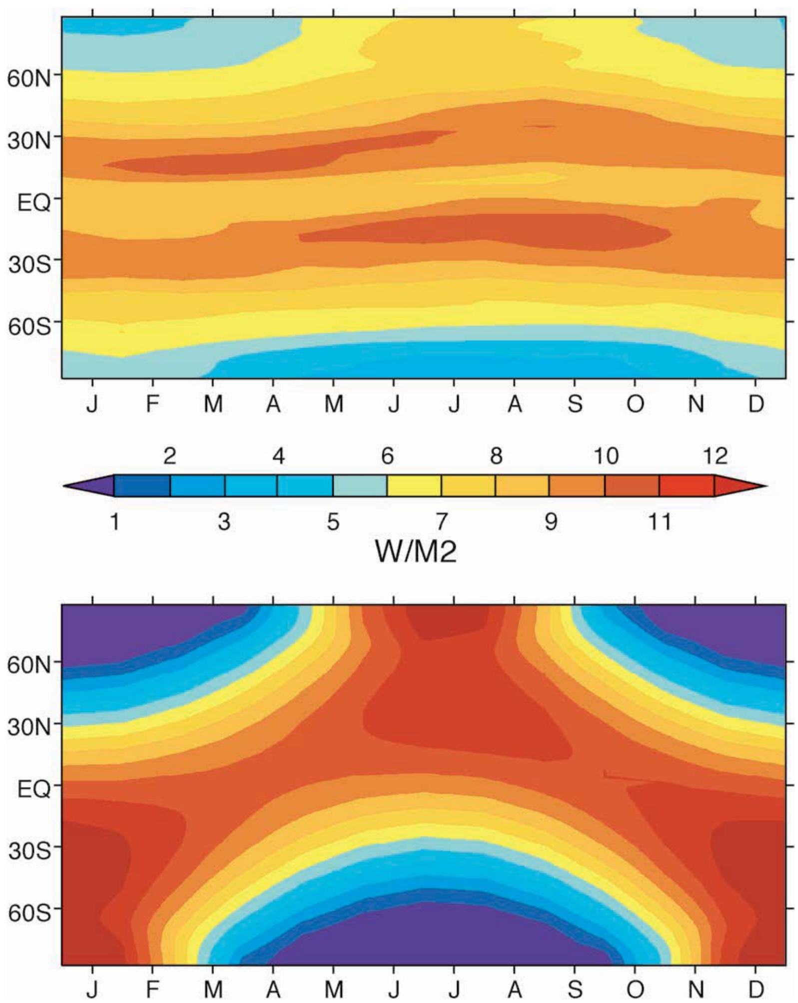

Figure 3.4: Radiative Flux at the Tropopause from Govindasamy and Caldeira (2003)
The top panel shows the change in net long-wave radiative flux [W m^{-2}] anomaly at the tropopause in Govindasamy and Caldeira's (2003) 4 × CO_2 experiment, relative to a preindustrial control, where the sign convention is such that positive flux is directed downward, toward thesurface . The bottom panel shows the reduction of insolation at the tropopause needed to offset in the global mean, the forcing in the top panel.

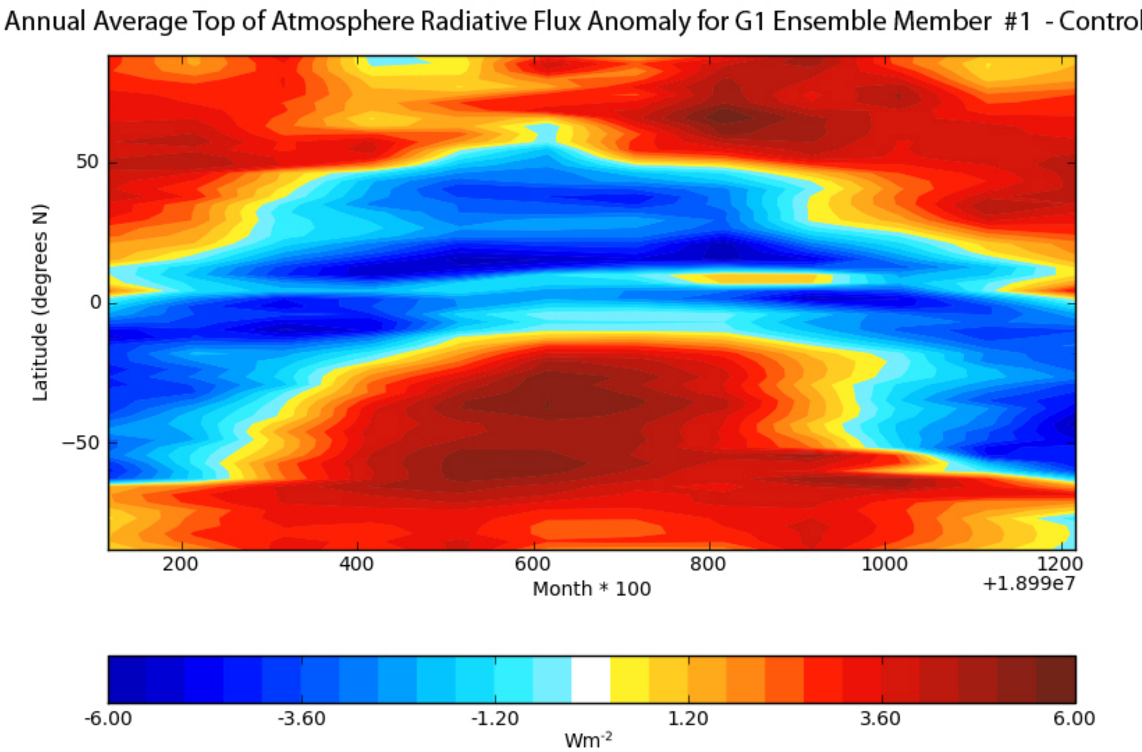

Figure 3.5: G1 Top of Atmosphere Radiative Flux Anomaly
(Image provided by Charles Curry.)

The annual means from the G1 experiment in this study can be compared with the patterns of the precipitation and temperature anomalies (experimental minus control) from the experiment conducted by Lunt et al. (2008), in which, as with the G1 experiment, a quadrupling of atmospheric carbon dioxide concentrations (relative to a preindustrial control) is offset by a reduction of the solar constant.

3.1.2 G1 GEOGRAPHIC AND SEASONAL TEMPERATURE DIFFERENCES

The temperature anomalies in the G1 experiment show a latitudinal variation (Figure 3.6) that can be explained by examining the latitudinal variation of the forcing. During the geoengineering period, the decrease in the solar constant is reducing the incoming solar radiation (primarily shortwave) over the Earth's surface, while the increased greenhouse gas concentration is increasing the longwave forcing. As mentioned above, because the tropics experience the greatest amount of incoming solar radiation, whereas the high latitudes experience the least amount of incoming solar radiation, the overall effect is a preferential cooling in the tropics and a warming in the high latitudes.

Similar to the findings of Lunt et al. (2008), most of the cooling occurs over the ocean in the tropics, subtropics and lower mid-latitudes (Figure 3.6; Figure 3.7). The pattern of warming over the Antarctic regions are quite similar to those of Lunt et al. (2008), with a warming of 0.4 K to 0.8 K throughout much of the region, extending out into the Weddell and Bellingshausen Seas. The area with the greatest warming is over the Bering, Chukchi and East Siberian Seas as well as the Arctic Ocean. Again, this is in agreement with Lunt et al. (2008). Warming is also seen over northern high latitude continents, including northern Asia, northern Europe, the northern portion of North America (most of Canada) and Greenland.

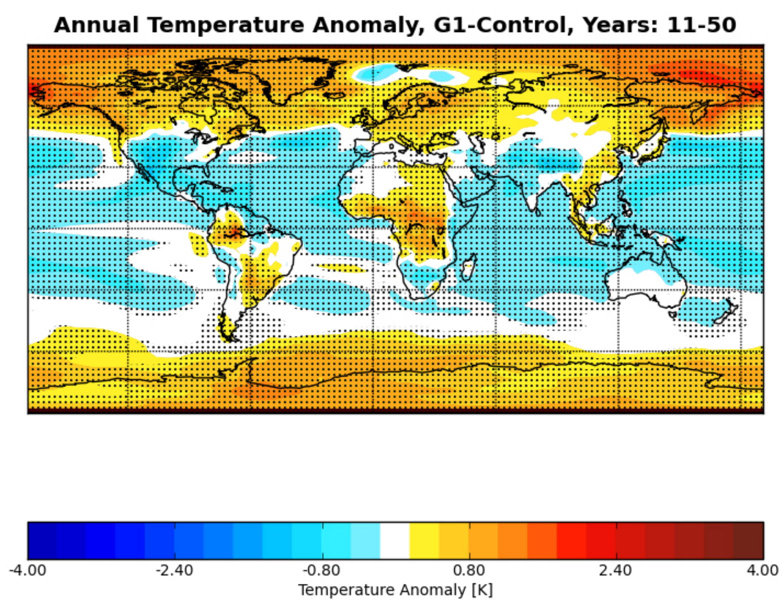

Figure 3.6: G1 Annual Temperature Anomaly, Years 11-50
Stippling indicates regions of statistical significance where $p < 0.05$ as determined by a t-test.

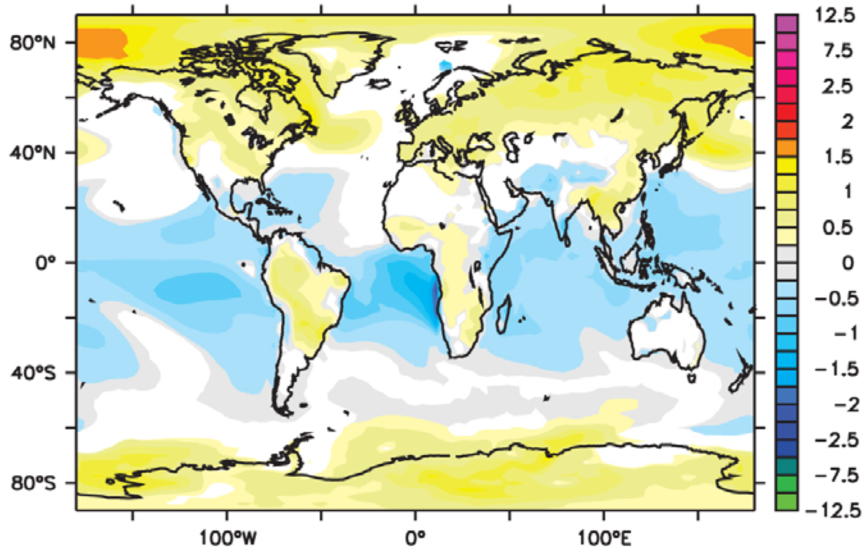

Figure 3.7: Annual Temperature Anomaly, Lunt et al.
Change in 2 m air temperature (K) temperature, adapted[7] from Lunt et al.'s (2008) "sunshade" geoengineering experiment(4 × CO2 being offset by a reduced solar constant vs. a preindustrial control).

The temperature anomalies are much smaller in the G1 experiment (Figure 3.6) than they are in the 4 × CO_2 experiment (Figure 3.8). Both the 4 × CO_2 experiment and G1 show polar amplification, though in the 4 × CO_2 experiment, there is warming everywhere, whereas the G1 experiment shows cooling over most of the tropical and midlatitude oceans.

[7] In the original plots from Lunt et al., nondescript grays filled the region in the temperature plots, from -0.5 to 0.5 and similarly for the precipitation plots, between -0.2 and 0.2. Hence, the colours were remapped for ease of comparison.

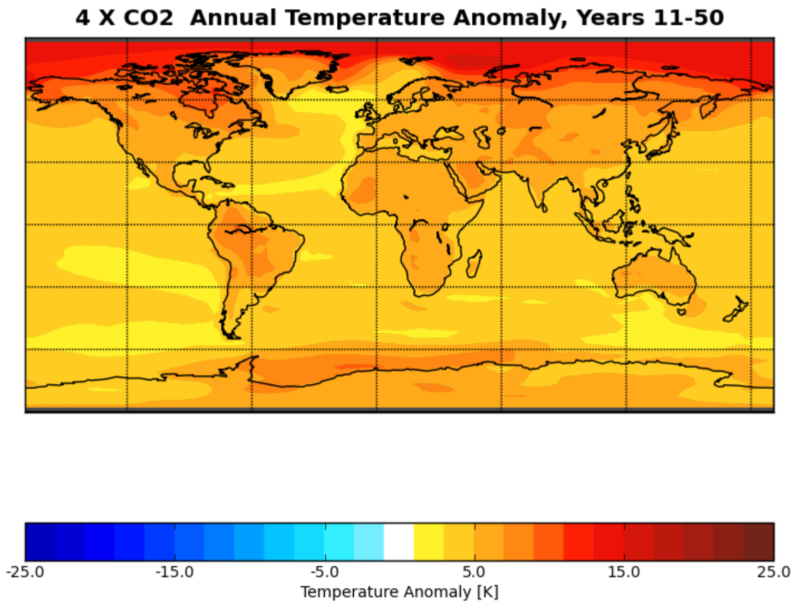

Figure 3.8: Temperature Anomaly, 4 X CO2 Experiment, Years 11-50

During the DJFM period (Figure 3.9), a sizable warming occurs over the poles, particularly pronounced over northern high latitudes, a seasonal increase that is likely due, in part, to the latitudinal variation of the net forcing, which is dominated by the longwave component at this time and location (Figure 3.4). Warming also occurs over most of Africa, Europe, Eastern and Western Asia. Cooling is evident over the ocean in the tropics and mid-latitudes. Over the continents, cooling occurs over India, most of the United States, Central America, Northern Asia, Western Australia, the southern tip of Africa and the western coast of South America.

During the JJAS period (Figure 3.10), the pattern of overall cooling in the tropics and warming at the poles is again apparent, though warming is most intense in the Southern Hemisphere. Cooling is visible over Northern Africa, Southern Africa, Northern Australia and large parts of North America, though the northernmost area, including much of BC, the Yukon and Alaska, as well as the east coast of Canada, experience warming.

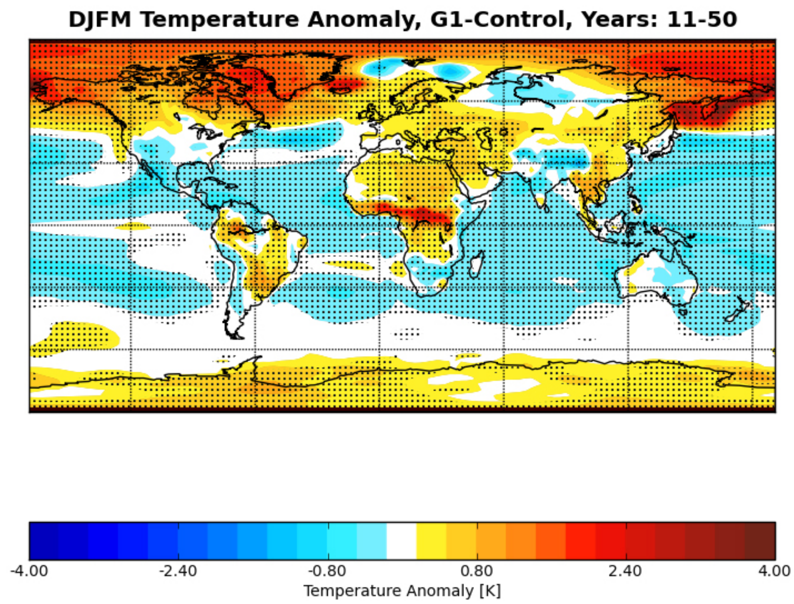

Figure 3.9: G1 DJFM Temperature Anomaly, Years 11-50

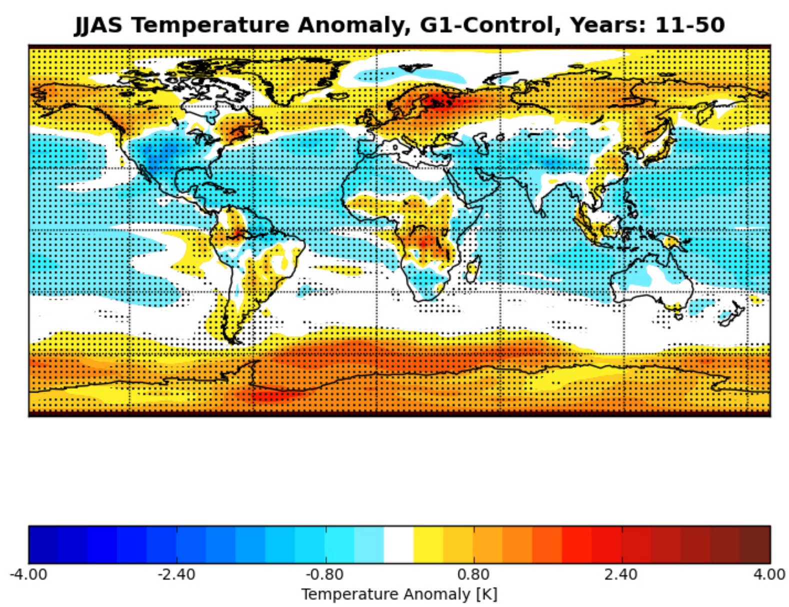

Figure 3.10: G1 JJAS Temperature Anomaly, Years 11-50

3.2 Precipitation Changes: G1 versus Preindustrial Control

3.2.1 G1 ANNUAL MEAN GLOBAL AND ZONAL PRECIPITATION RESULTS

In the G1 experiment, during the geoengineering period, there is an overall decrease in global precipitation, of roughly -3.84 millimeters per month, or roughly 4.67% (Figure 3.11). This is generally similar to runs using the same overall experimental design (4xCO2 offset by solar constant reduction), which resulted in overall decreases in global precipitation of 5% (Lunt et al., 2008) and roughly 3% (Govindasamy and Caldeira, 2003).

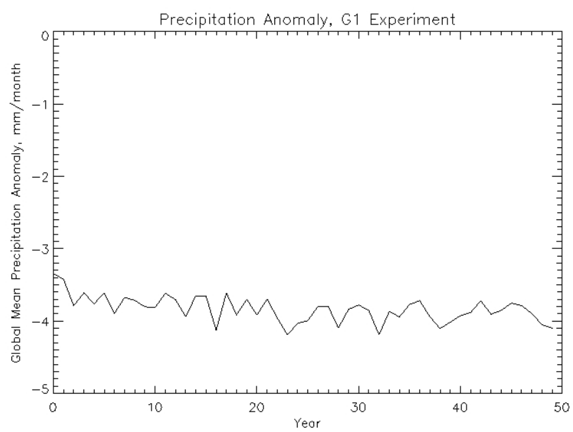

Figure 3.11: G1 Annual Mean Precipitation Anomaly, Years 0-50
Global mean precipitation anomaly, G1 – control [mm month^{-1}].

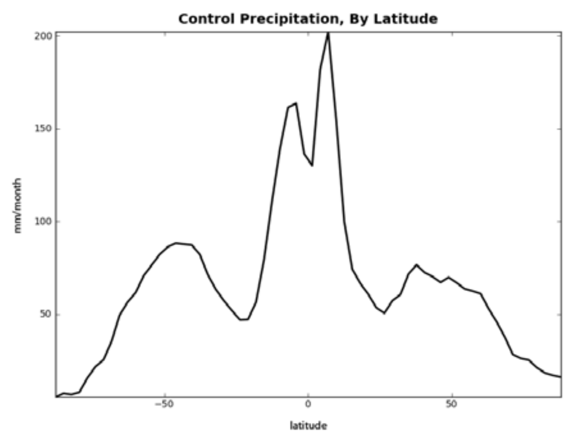

Figure 3.12: Precipitation in Control Run, by Latitude
Mean precipitation by latitude in preindustrial control run [mm month^{-1}].

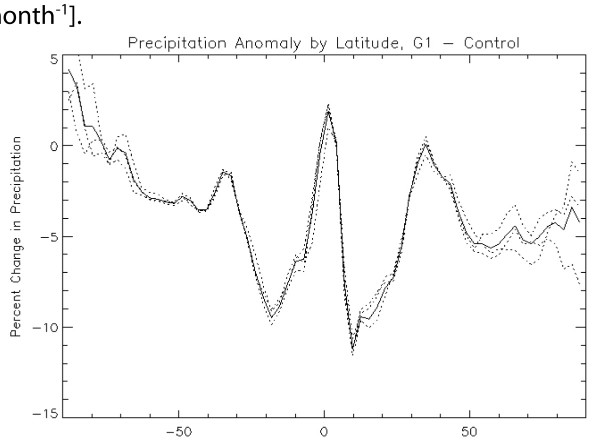

Figure 3.13: G1 Annual Mean Precipitation Anomaly by Latitude, Years 11-50
Solid line represents model ensemble and thin, dashed lines represent individual ensemble members.

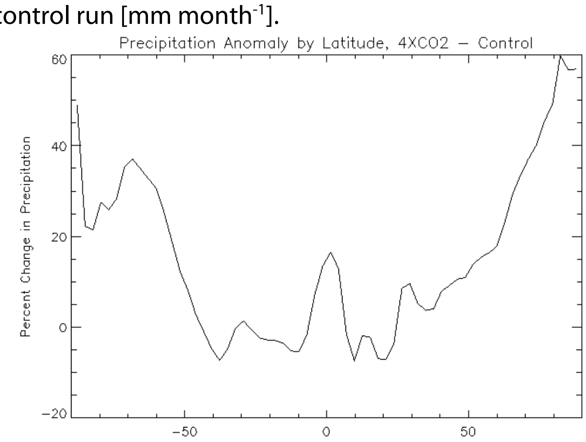

Figure 3.14: 4×CO_2 Annual Mean Precipitation Anomaly by Latitude

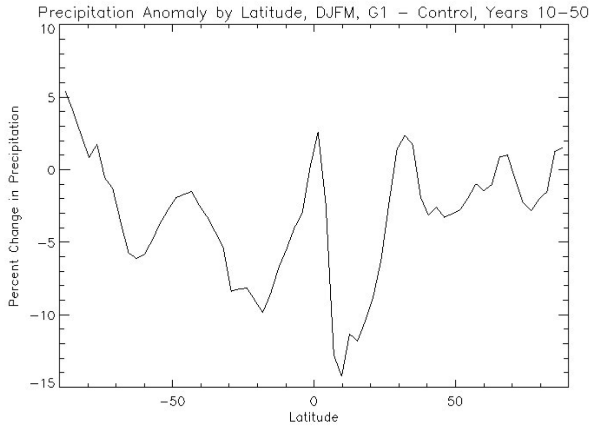

Figure 3.15: G1 Annual Mean Precipitation Anomaly by Latitude, DJFM, Years 10-50

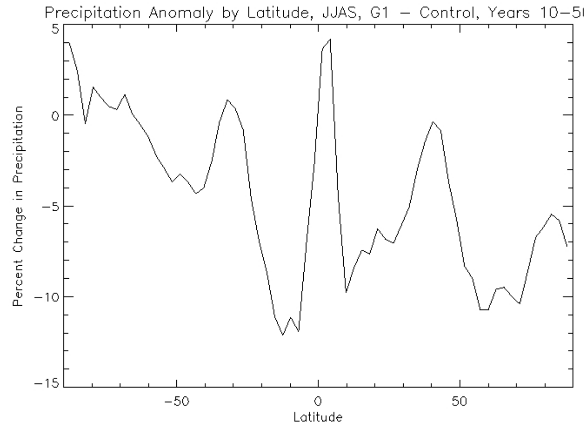

Figure 3.16: G1 Annual Mean Precipitation Anomaly by Latitude, JJAS, Years 10-50

First, it should be noticed that the precipitation in the control run (Figure 3.12) demonstrates a split Intertropical Convergence Zone (ITCZ). This is a known defect in certain climate models (Randall et al., 2007) which will make precipitation differences here more difficult to interpret. In the zonal means of the precipitation for the 4 × CO_2 run, a relatively large increase in precipitation relative to the preindustrial control climate is apparent (Figure 3.14). It is most pronounced in high latitude regions and surrounding the equator. Evident in the G1 data during the period of years 11-50 (Figure 3.13), there is an overall decrease in precipitation, most pronounced in the tropics. This follows from the analyses of Allen and Ingram (2002) and Bala et al. (2008) above.

In the G1 experiment, for the annual means over years 11-50, there is an overall decrease in precipitation, except for a slight increase in precipitation in the ITCZ over the Pacific Ocean (Figure 3.13). The decrease in precipitation over the tropical ocean outside of the ITCZ and the tropics, especially over much of Africa, is particularly pronounced (Figure 3.13).

Overall, the pattern of the precipitation anomaly shown in Figure 3.13, which features an increase near the ITCZ, decreased precipitation in tropics and lower midlatitudes and slightly increased precipitation in high latitude Southern Hemisphere bears some similarity to the similar experiments conducted by Lunt et al. (2008) and Ban-Weiss and Caldeira (2010). Although there is high variability in the polar regions, the ~ 5% increase visible in the zonal means near the poles in the G1 run is significant, as will be shown in the spatial plots, below. Lunt et al. find a similar increase in precipitation—albeit, more northerly in location—and attribute this to a reduction in the meridional temperature gradient, which causes the ITCZ to shift northward. Ban-Weiss and Caldeira (2010) also find a spike in precipitation at the equator for their aerosol geoengineering with carbon dioxide doubling runs.

3.2.2 G1 ZONAL MEAN RESULTS: A CLOSER LOOK

This physical mechanisms underpinning the overall global mean decrease in precipitation (to wit: the ability of the troposphere to radiate away latent heat and the fact that changes to the solar forcing dominate equivalent changes to the greenhouse gas forcing in changing the surface latent heat flux) are discussed in some detail the hydrological impacts section (Section 1.7.7), above. The spike in the precipitation anomaly over the ITCZ cannot be due directly to the combination of the reduced solar forcing and increased greenhouse gas forcing, which should, as discussed earlier, lead to a reduction in precipitation over the tropics.

To make sense of these patterns, one might first try applying the simple thermodynamic model of Held and Soden (2006), who were able to explain much of the meridional structure of the zonal means of precipitation observed in increased greenhouse gas experiments.

Working from the Clausius-Clapyron (CC) equation for saturation vapour pressure and the assumption that the background flow is unchanged, Held and Soden (2006) propose that the change in the time-averaged, vertically-integrated, horizontal vapour transport, F scales with the saturation vapour pressure only. (In other words, as the global mean temperature rises, the water vapour in the lower troposphere increases, and it is this increase in water vapour in the lower troposphere that is responsible for the increase in horizontal vapour transport, not changes in the atmospheric flow field.) So, precipitation minus evaporation is equal to the negative divergence of F, $(P - E) = -\nabla \cdot F$. So, if F is scaled by some constant factor, P-E is scaled by the same factor. Hence, the most important variable affecting F is the tropospheric mixing ratio. Further assuming that there are no changes in relative humidity (a reasonable approximation over the ocean and land regions with significant water content) and that the change to temperature, δT, has less zonal structure than P - E, then P - E scales with the Clausius-Clapyron equation as follows:

$$\delta(P - E) = \alpha \delta T (P - E) \qquad \textbf{Equation 3.1}$$

Where $\alpha \approx 0.07 K^{-1}$. So, as Held and Soden note: "[t]he pattern of P - E is simply enhanced, becoming more positive where it is already positive and more negative where it is [already] negative." Figure 3.17 shows that the overall structure of the response to an increased greenhouse gas forcing is captured by the simple arguments above.

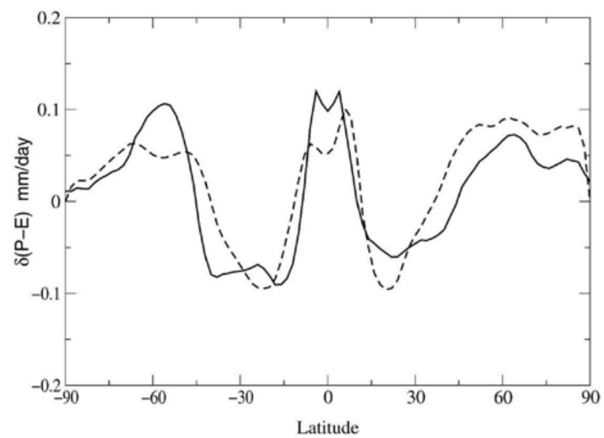

Figure 3.17: Precipitation Minus Evaporation Anomaly by Latitude from Held and Soden (2006)
Precipitation Minus Evaporationanomaly by latitude [mm/day] from Held and Soden (2006). The solid line represents simulations from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) models for the IPCC's AR4 and the dashed line represents the thermodynamic component, predicted from Equation 3.1.

However, upon examination, this simple thermodynamic model does not explain the results from the GeoMIP experiment. Consider that, over the ITCZ, P – E is positive (Figure 3.18), the change in P – E is positive (Figure 3.19) and the change in temperature (Figure 3.2) is negative. Hence, Equation 3.1 does not hold and the simple thermodynamic model given by Held and Soden (2006) does not apply to the GeoMIP experiment. Clearly other factors, which might include a change in the stability, vertical profile or circulation of the atmosphere, are at play here.

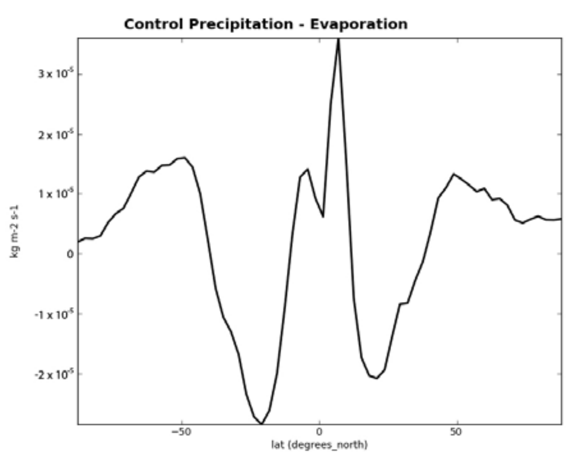

Figure 3.18: Control Precipitation - Evaporation

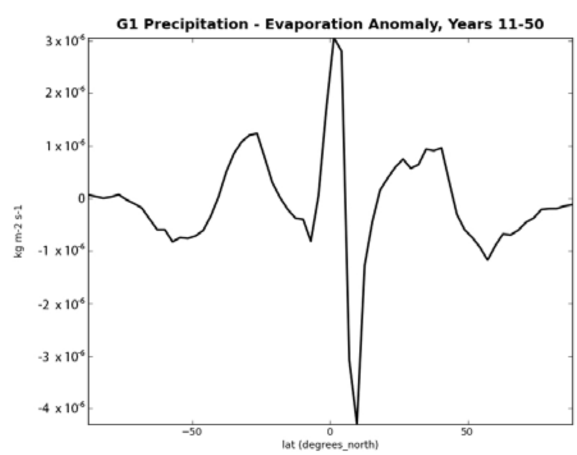

Figure 3.19: G1 Precipitation - Evaporation Anomaly, Years 11-50

In their attempt to optimize geoengineering through varying the simulated zonal distribution of sulfate aerosols, Ban-Weiss and Caldeira (2010) find that, even if the aerosols are distributed such that the zonal temperature anomaly is minimized, there are significant changes in the zonal anomaly of P – E (Figure 3.20).

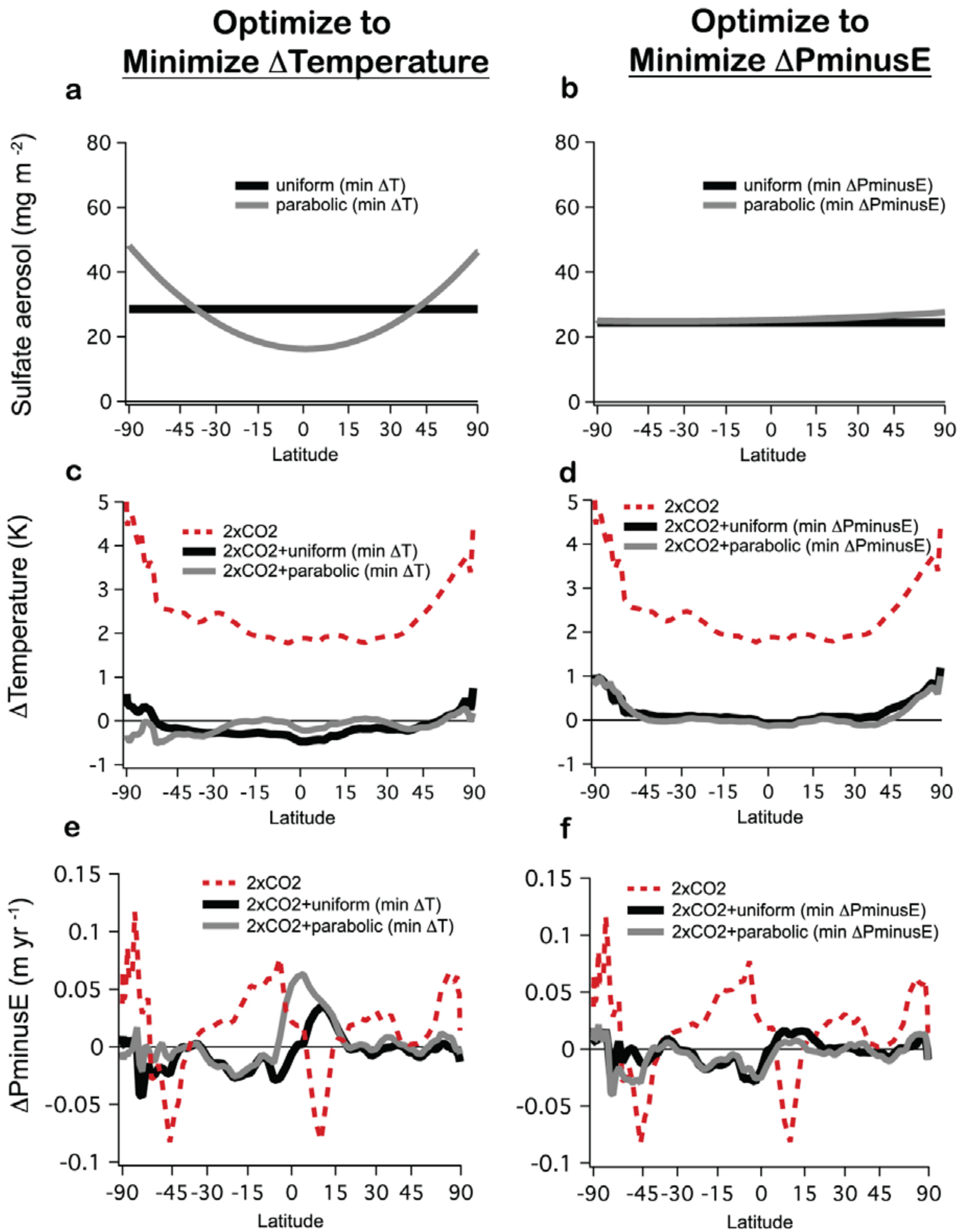

Figure 3.20: Temperature and Hyrdological Optimization, from Ban-Weiss and Caldeira

Here, the left column shows Ban-Weiss and Caldeira's (2010) attempt to minimize the change in temperature in a 2 × CO_2 simulation, relative to a preindustrial control climate (1 × CO_2). The right column shows a similar attempt to minimize the change in precipitation minus evaporation (P – E). Here, a and b are zonal aerosol distributions; c and d are annual mean zonal temperatures and e and f are the corresponding changes to P – E.

In Ban-Weiss and Caldeira (2010), the increased P – E anomaly near the equator (Figure 3.20e) is attributed to the northward shift of the ITCZ. It is not clear that the ITCZ shifts in the G1 experiment and hence, it is not clear that the explanation offered by Ban-Weiss and Caldeira (2010) will hold here. However, Ban-Weiss and Caldeira's results do show that the simple model of Held and Soden (2006) does not hold for at least one other instance of stratospheric sulfate aerosol geoengineering. The cause of the increased precipitation over the ITCZ in the GeoMIP experiment remains an open question.

3.2.3 G1 GEOGRAPHIC AND SEASONAL PRECIPITATION DIFFERENCES

In the annual mean, the pattern of overall reduced precipitation, especially over the tropics, and increased precipitation in the Intertropical Convergence Zone (ITCZ) over the Pacific Ocean remains (Figure 3.21). The precipitation increase over South-Western Asia is prominent. Both the results here and Lunt et al. (2008) show the ITCZ strengthened (Figure 3.21; Figure 3.22), but Lunt et al.'s results, it is shifted northward, due to an increased meridional temperature gradient (Lunt et al., 2008). As with this study, they also find a slight decrease in precipitation over northern and eastern North America, and they find that changes to precipitation in the mid and high latitudes are relatively small, which is consistent with the results shown here. Also consistent with Lunt et al. (2008) is the pattern of stronger precipitation changes over the ocean than over land.

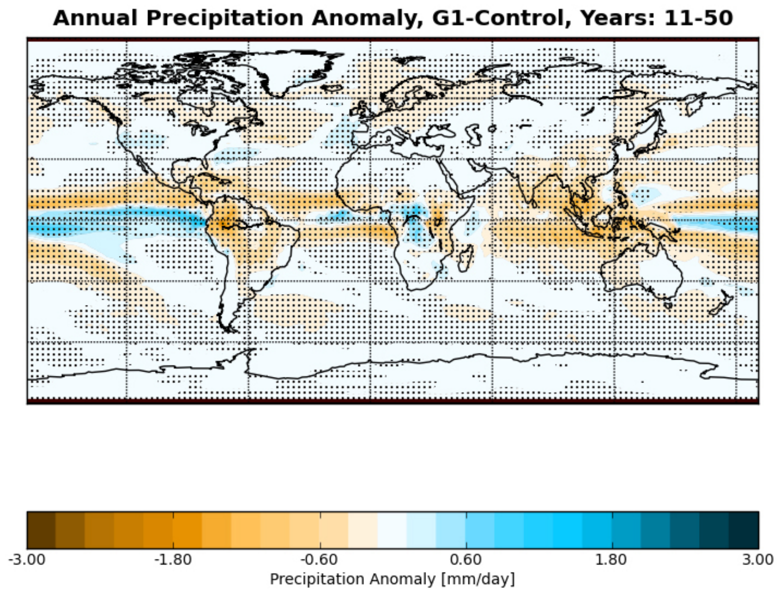

Figure 3.21: G1 Annual Absolute Precipitation Anomaly, Years 11-50

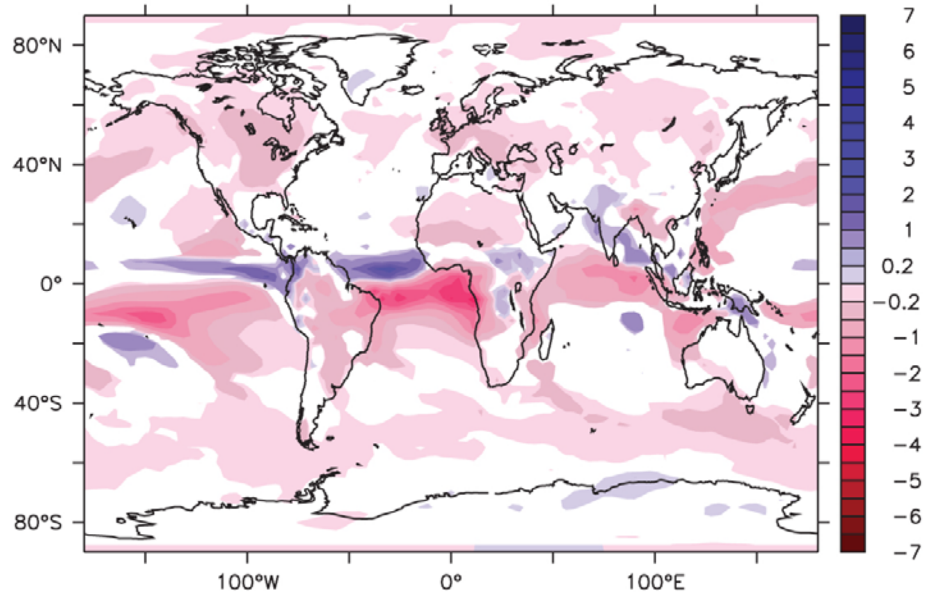

Figure 3.22: Annual Precipitation Anomaly, Lunt et al., 2008

Annual absolute precipitation anomaly [mm day^{-1}] adapted from Lunt et al. (2008).

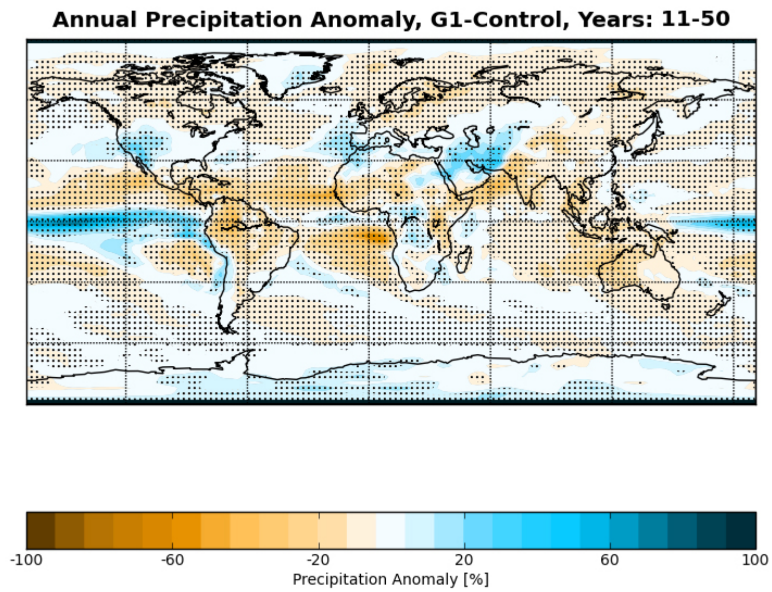

Figure 3.23: G1 Annual Percent Precipitation Anomaly, Years 11-50

Regionally, the precipitation changes are much smaller in the G1 experiment (Figure 3.23) than they are in the 4 × CO_2 experiment (Figure 3.24), though the global changes in precipitation are of comparable magnitude because of the overall drying in the tropics in G1 (Figure 3.13). There are some similarities in the tropical region between G1 and the 4 × CO_2 experiment, with increased precipitation over the ITCZ and drying in the subtropics, outside of that area, the similarities end, with G1 showing mostly decreased precipitation over the mid and high latitudes and the 4 × CO_2 experiment largely showing increased precipitation.

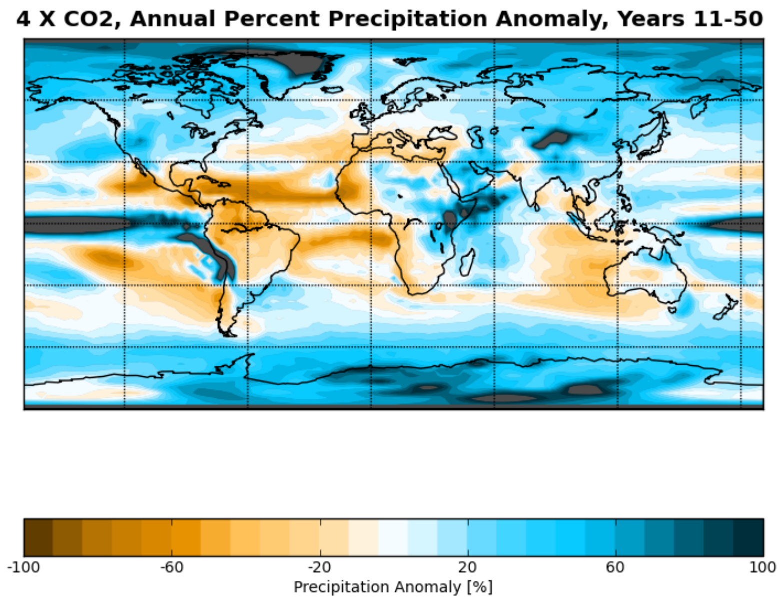

Figure 3.24: Percent Precipitation Anomaly, 4 X CO2 Experiment, Years 11-50

During the DJFM period, there is pronounced drying (Figure 3.25) across Central Africa, Australia, north and south of the equator over most of the Atlantic, the northern part of South America (extending from Venezuela south, to Southern Brazil and Paraguay). Most of the changes appear to be larger over land. There is an increase in precipitation across the Middle East and a slight reduction in precipitation across Northern Europe. In the seasonal zonal means (not shown) there is a reduction in precipitation across the Northern Tropics and an increase in precipitation in the high northern latitudes.

Over the JJAS period, the strengthening of precipitation in the ITCZ over the Pacific Ocean is particularly pronounced, but an overall drying over the tropics is still evident (Figure 3.26). Precipitation also increases over Central South America, eastern Australia, part of Western Asia and southwestern North America. There is a slight decrease in precipitation over Asia taken as a whole. This could indicate a weakening of the Asian Monsoon. All of Europe experiences a decrease in summer precipitation, as does Northern Russia.

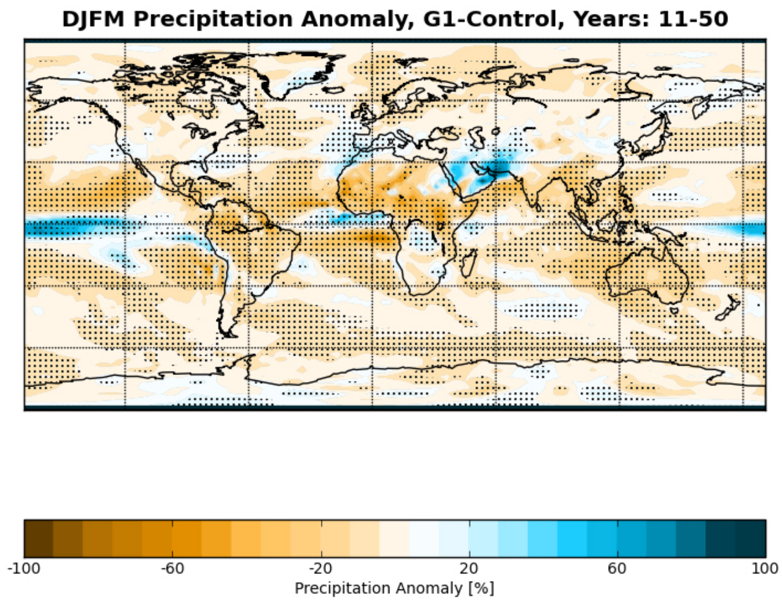

Figure 3.25: G1 DJFM Precipitation Anomaly, Years 11-50

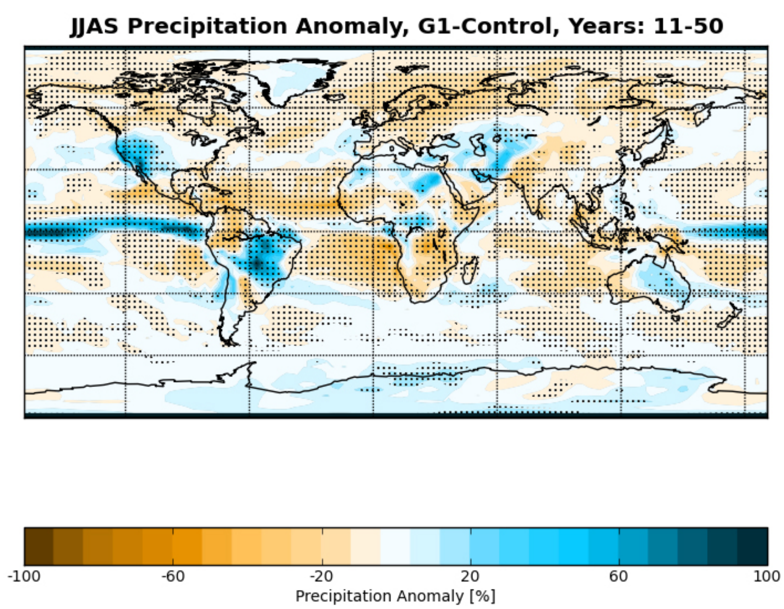

Figure 3.26: G1 JJAS Precipitation Anomaly, Years 11-50

3.3 Temperature Changes: G2 versus Preindustrial Control

3.3.1 G2 ANNUAL MEAN GLOBAL AND ZONAL TEMPERATURE RESULTS

As with the G1 experiment, during the geoengineering period for G2, there is negligible warming, globally (Figure 3.27). The anomaly of the zonal mean of annual temperature (Figure 3.28) shows some similarity to that of G1, with cooling over most of the tropics, minimal cooling over the equator and warming in the higher latitudes, though the similarity diminishes near the South Pole, a region of high variability (Figure 3.28).

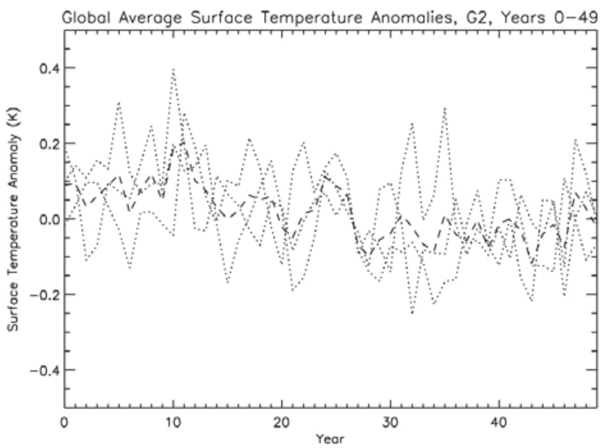

Figure 3.27: G2 Global Average Surface Temperature Anomalies, Years 0-49
The solid, dashed line indicates the ensemble mean, and the light, dotted lines represent individual ensemble members.

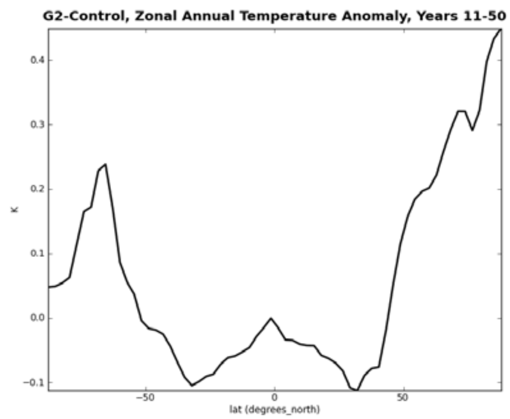

Figure 3.28: G2 Zonal Annual Temperature Anomaly, Years 11-50

3.3.2 G2 GEOGRAPHIC AND SEASONAL TEMPERATURE DIFFERENCES

The spatial distribution of warming and cooling found here for the G2 experiment (Figure 3.29) matches quite closely that of the G1 experiment (Figure 3.6), although the change in the meridional temperature gradient is smaller than in G1, with the mid latitudes cooling less and the high latitudes warming less.

The annual means from the G2 experiment in this study can be compared to the experiment conducted by McCusker et al. (2012), in which atmospheric carbon dioxide concentrations were increased, by 1% per year, to a doubling (relative to a preindustrial control). As in G2, McCusker et al.'s experiment involved gradually reducing the solar constant in order to offset the forcing from the increasing atmospheric GHG concentration. It is important to note that, whereas the G2 experiment varies from 112% to164% of preindustrial atmospheric carbon dioxide concentrations during the geoengineering period from which the results here have been taken, the plots from McCusker et al.'s experiment show a period of roughly 2 × CO_2 (McCusker et al., 2012).

Comparing the annual temperature anomaly (Figure 3.29) to McCusker et al. (2012), the G2 experiment shows warming in the Weddell Sea, whereas McCusker et al. (Figure 3.30) find a slight, but statistically significant cooling in this region. Both the results here and those of McCusker et al. show the greatest warming over the region comprised of the Beaufort, Chukchi and East Siberian Seas and Arctic Ocean. However, McCusker et al. find the greatest warming to be centered in the East Siberian Sea, whereas the results here show the greatest warming to be centered in the Chukchi and Bering Seas. Both experiments show a slight cooling in the Barents and Norwegian Seas. The two experiments also differ in that G2 shows warming in the North Atlantic and over most of Greenland, whereas McCusker et al. find cooling in these regions.

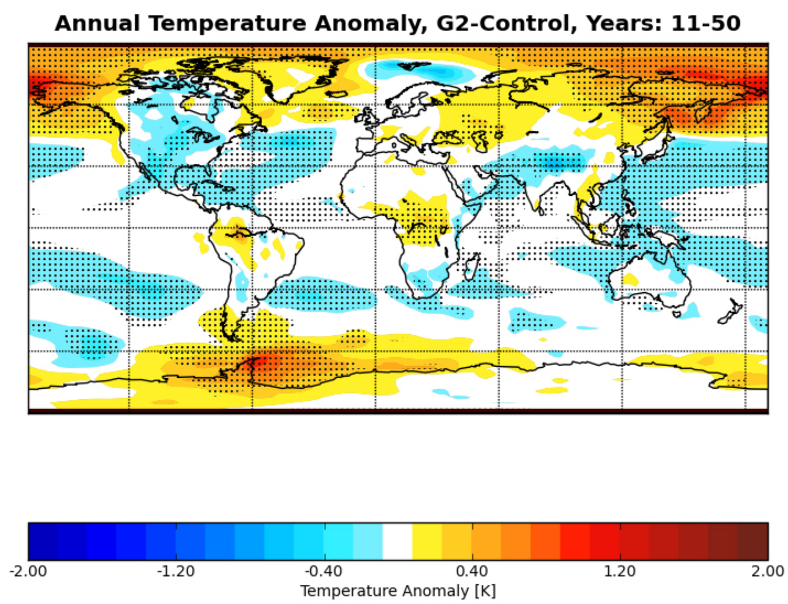

Figure 3.29: G2 Annual Temperature Anomaly, Years 11-50

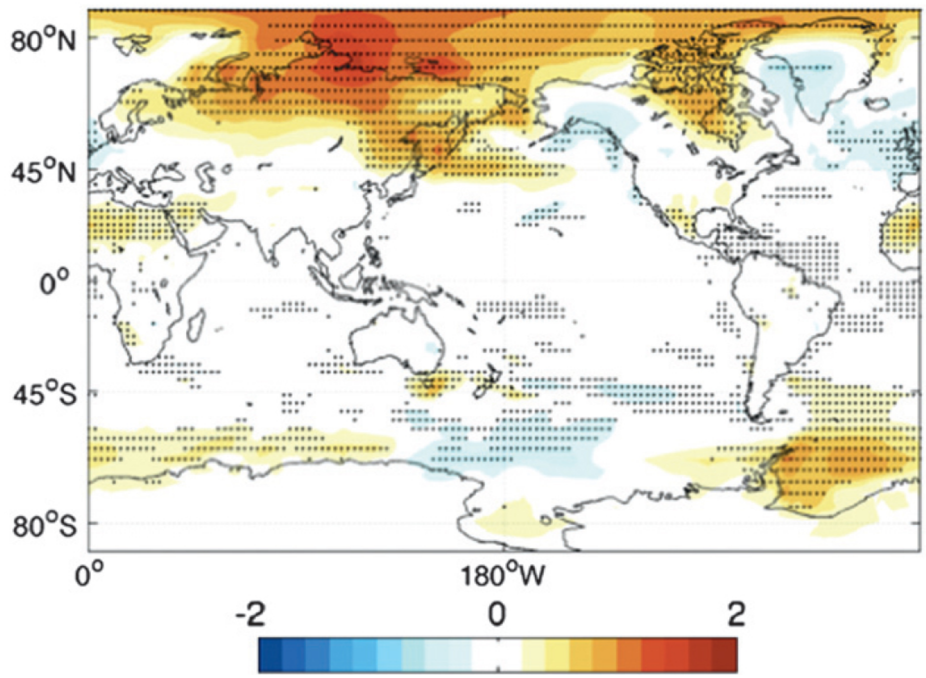

Figure 3.30: Global Temperature from McCusker et al. (2012)
Global temperature anomaly [K] from McCusker et al. (2012). Stippling indicates areas of 95% significance as determined by a Student's t-test.

The pattern of seasonal warming and cooling during the geoengineering period for G2 (Figure 3.31) in DJFM closely matches that of G1 (Figure 3.9). During the DJFM period for both experiments, polar amplification of the warming is noticeable, extending to northern high latitudes. This is likely due to the fact that, as discussed above, the surface air temperature response to the combined solar forcing decrease and greenhouse gas forcing increase preferentially warms higher latitudes while cooling lower latitudes. The same warming pattern as occurs in G1 is also seen over most of Africa, Europe, Eastern and Western Asia in the G2 experiment. Also noticeable is the same pattern of cooling as occurs in G1, albeit to a lesser extent, over the ocean in the tropics and mid-latitudes. Over the continents, cooling occurs over India, most of the United States, Central America, Northern Asia, Western Australia, the southern tip of Africa and the western coast of South America.

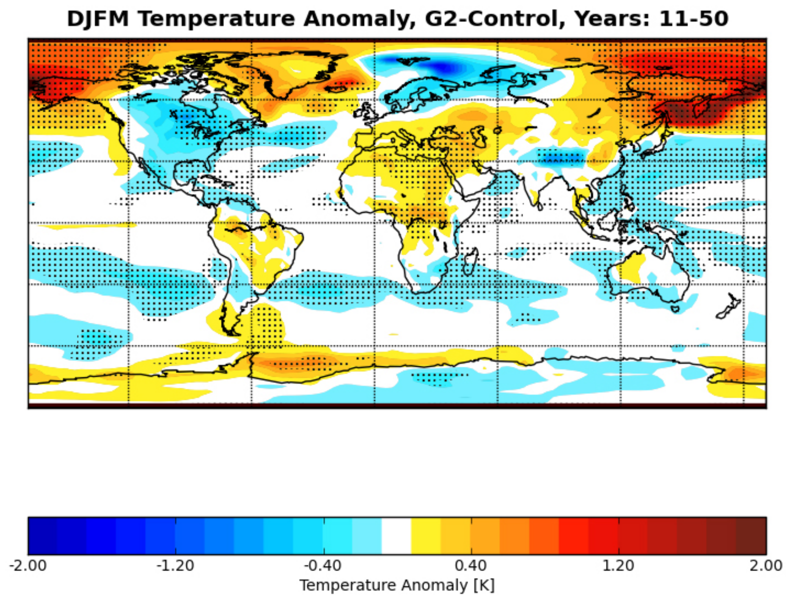

Figure 3.31: G2 DJFM Temperature Anomaly, Years 11-50

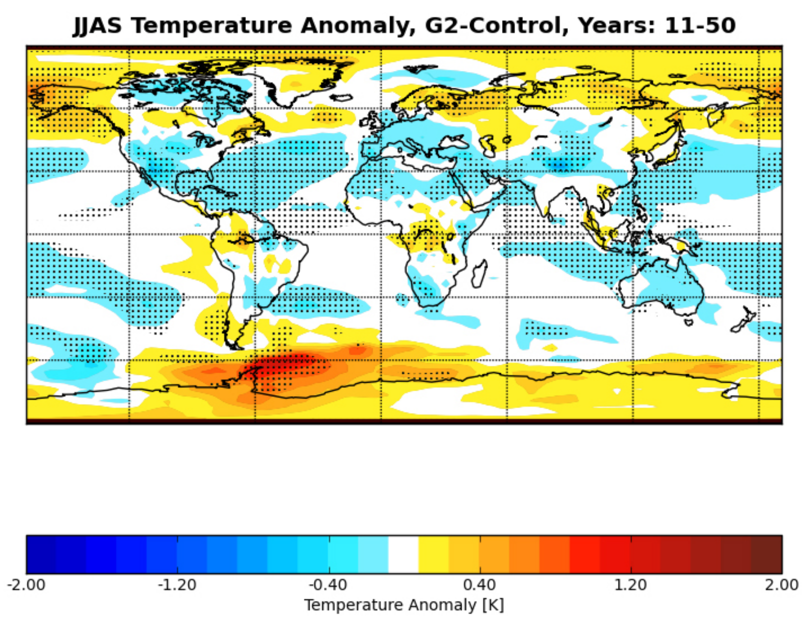

Figure 3.32: G2 JJAS Temperature Anomaly , Years 11-50

Similarly to the DJFM period, during the JJAS period the pattern of seasonal warming and cooling for the geoengineering period for the G2 experiment (Figure 3.32) closely matches that of

G1 (Figure 3.10). Again, the meridional pattern of overall cooling in the tropics and extratropics and warming at the poles is apparent, with warming being most intense in the Southern Hemisphere; however, in the G2 experiment, the Antarctic Warming is most intense in a region more or less confined to the Weddell Sea, whereas in G1 it is apparent throughout much of the South Atlantic. Again, similarly to G1, in the G2 experiment, similar cooling is visible over Northern Africa, Southern Africa, Northern Australia, America and large parts of North America, and a similar warming over the West Coast of North America, the Yukon and Alaska, as well as the East Coast of Canada.

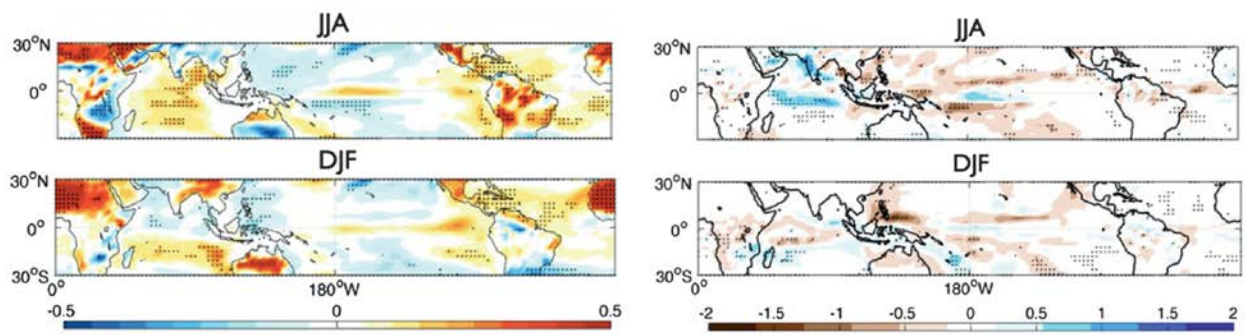

Figure 3.33: Seasonal Temperature and Precipitation from McCusker et al. (2012)
Seasonal (DJF and JJA) temperature [K] and precipitation [mm/day] anomalies from McCusker et al. (2012)

Some care must be taken in the comparing of the seasonal anomalies of both temperature and precipitation (Figure 3.31; Figure 3.32; Figure 3.38; Figure 3.39) to those of McCusker et al. (Figure 3.33). First, McCusker et al. have cropped their plots to the region between the latitudes of 30° south to 30°north. Second, McCusker et al.'s findings show small areas of statistically significant change. Third, the seasons that McCusker et al. show are DJF and JJA, whereas the results here for G2 are for DJFM and JJAS.

With these caveats in mind, in Northern Hemispheric winter, both McCusker et al.'s experiment and the results from the G2 run show warming over Northern Africa, Southeast Asia and some of Northern Australia. However, while the G2 experiment displays cooling over the southern part of North America, McCusker et al. find warming.

In Northern Hemisphere summer, McCusker et al. find warming over Northern Africa and South Africa, whereas the G2 run shows cooling in these regions. There is some agreement to be found in the warming over northeastern South America, but generally McCusker's findings do not match those of G2.

3.3.2 G2 ANNUAL MEAN GLOBAL AND ZONAL PRECIPITATION RESULTS

As with the G1 experiment, during the geoengineering period for G2, there is an overall decrease in global precipitation. For G2, this is roughly -0.635 millimeters per month, or approximately 0.772%. The anomaly of the zonal mean of precipitation shows some similarity to that of G1, with overall decreases in the subtropics and a slight increase over the ITCZ (Figure 3.34). The P – E anomaly (Figure 3.35) shows that the precipitation spike over the ITCZ cannot be explained using the simple model of Held and Soden (2006). The reasoning is the same as for the precipitation spike over the ITCZ in the G1 experiment, as explained in Section 3.2.2.

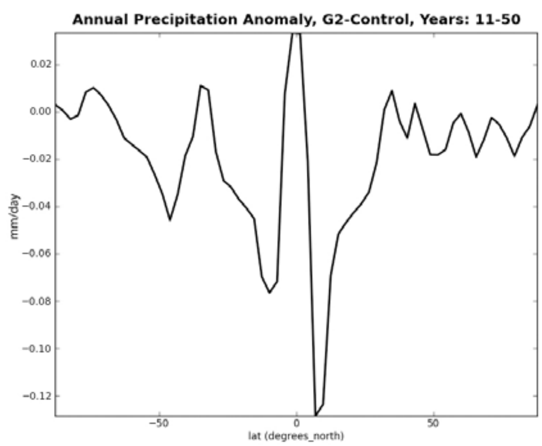

Figure 3.34: G2 Zonal Annual Precipitation Anomaly, Years 11-50
Zonal annual precipitation anomaly [mm/day], G2, years 11-50

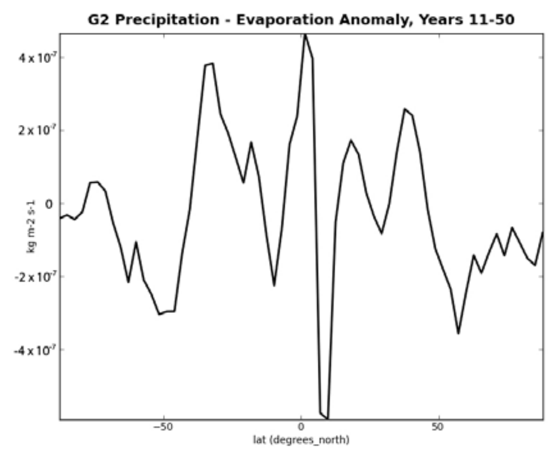

Figure 3.35: G2 Precipitation - Evaporation Anomaly, Years 11-50

3.3.3 G2 GEOGRAPHIC AND SEASONAL PRECIPITATION DIFFERENCES

Owing to the minimal amount of statistically significant change in McCusker et al.'s precipitation (Figure 3.33), no comparisons can be drawn between their results and the results presented here.

The pattern of the precipitation increases and decreases in G2 closely matches that of G1, both seasonally (Figure 3.25; Figure 3.26; Figure 3.38; Figure 3.39) and in terms of the annual mean (Figure 3.23; Figure 3.36), though the changes are smaller in magnitude for G2 and the areas of statistical significance are much smaller than in G1.

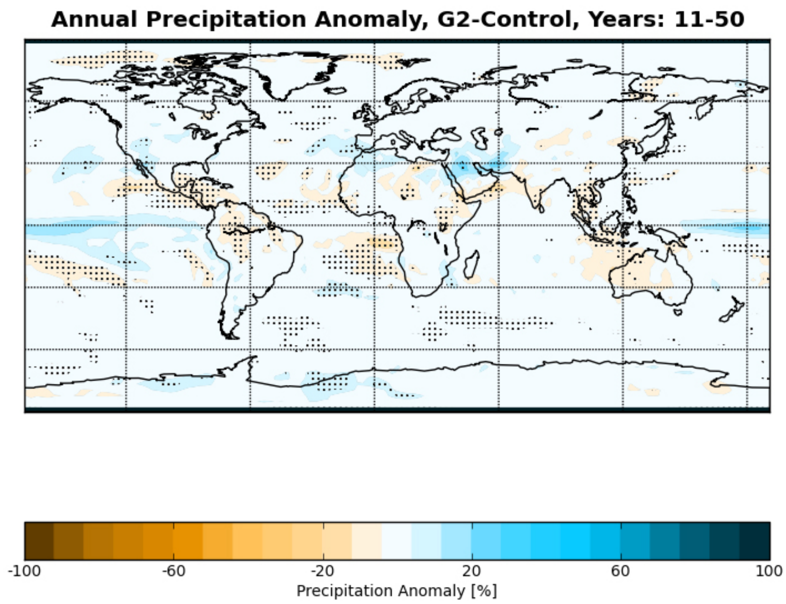

Figure 3.36: G2 Annual Precipitation Anomaly, Years 11-50

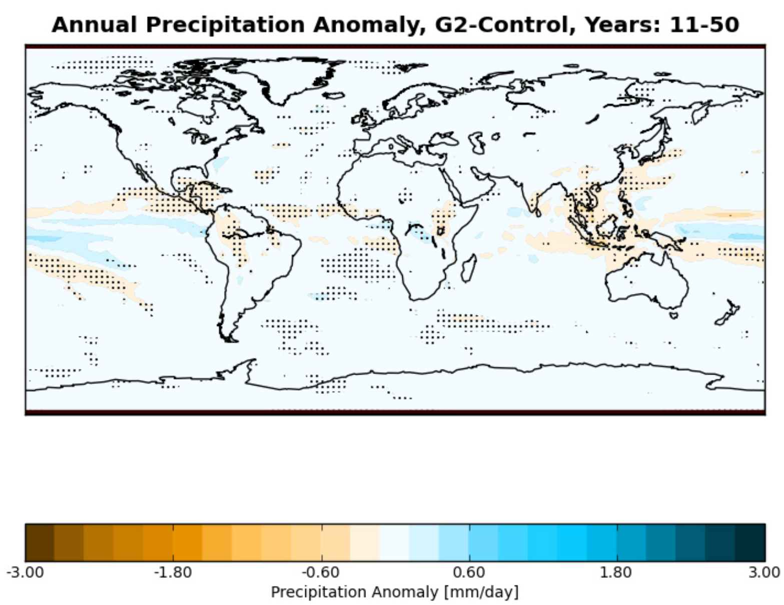

Figure 3.37: G2 Annual Precipitation Anomaly, Years 11-50 [mm/day]

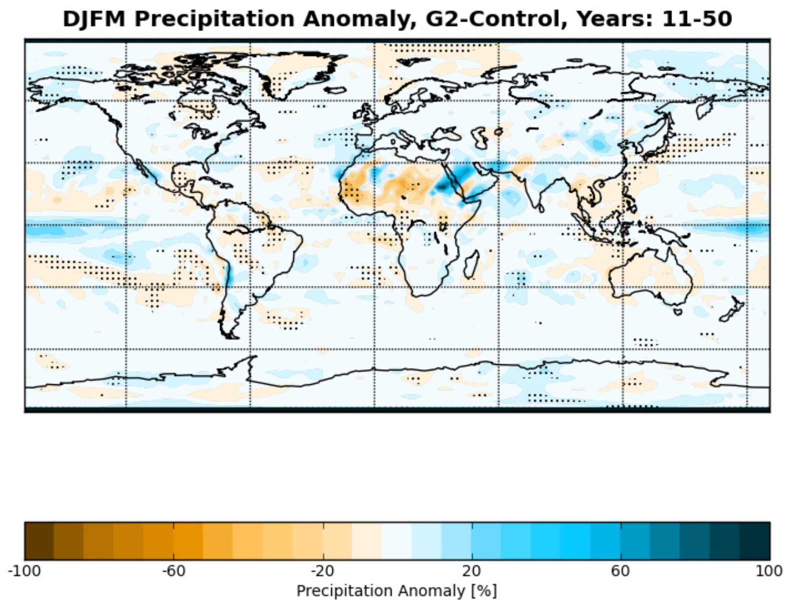

Figure 3.38: G2 DJFM Precipitation Anomaly , Years 11-50

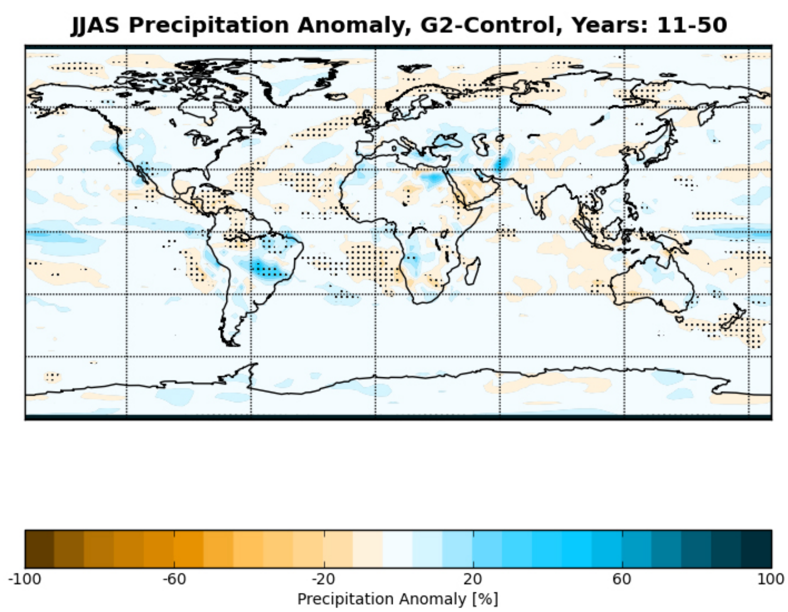

Figure 3.39: G2 JJAS Precipitation Anomaly , Years 11-50

4 Results from the Post-Geoengineering Period

4.1 G1: Post-Geoengineering Period

4.1.1 G1 GLOBAL MEAN CHANGES IN KEY CLIMATE VARIABLES POST-GEOENGINEERING

For G1 in the post-geoengineering period, many of the climatic variables for the G1 experiment shift rapidly toward the values of the 4 × CO_2 run, as can be seen for surface temperature, Northern and Southern Hemisphere Sea Ice Volume, Atlantic Meridional Overturning Circulation (AMOC) transport and precipitation (Figure 4.1 - Figure 4.6). This is sensible because, upon geoengineering termination, the system is immediately exposed to the increased forcing from the quadrupled carbon dioxide, which is no longer being offset by a solar constant decrease. Note that, toward the end of the experiment, 50 years following geoengineering failure, the runs tend toward those same values of the 4 × CO_2 run at year 50 (the red dotted lines in Figure 4.1 to Figure 4.6 highlight this). Ocean temperature (Figure 4.2) does increase, but more slowly than the other variables. Many of these anomalies do not start at exactly zero because the choice of control period which was used for comparison in this experiment does not exactly match the control period from which these runs were started.

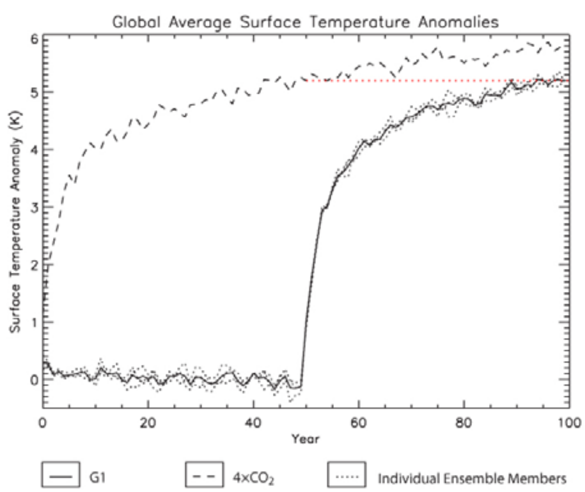

Figure 4.1: G1 Global Surface Temperature Anomaly
Global surface temperature [K] anomaly, G1 and 4 × CO_2 experiments

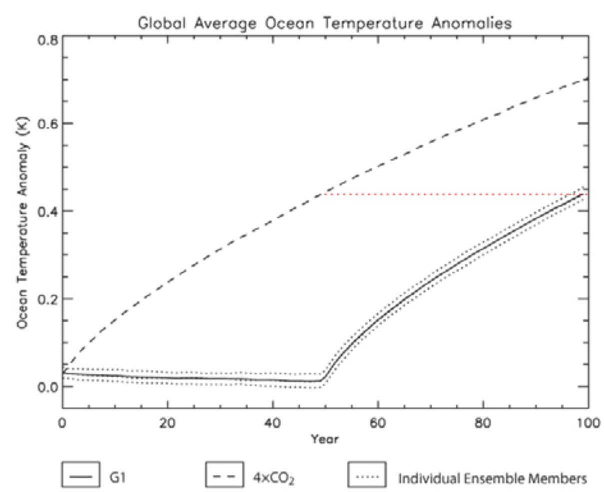

Figure 4.2: G1 Global Ocean Temperature Anomaly
Global ocean temperature [K] anomaly, G1 and 4 × CO_2 experiments

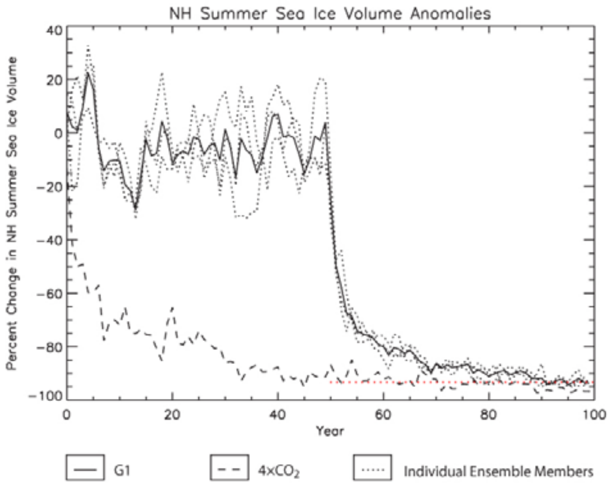

Figure 4.3: G1 NH Summer Sea Ice Volume Anomaly
NH summer sea ice volume [%] anomaly, G1 and 4 × CO_2 experiments

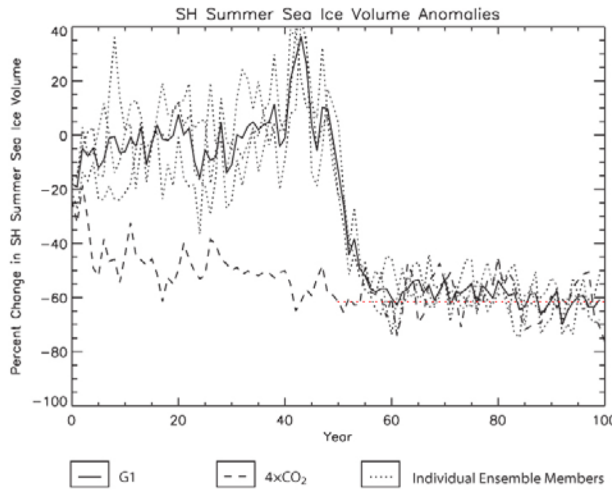

Figure 4.4: G1 SH Summer Sea Ice Volume Anomaly
SH summer sea ice volume [%] anomaly, G1 and 4 × CO_2 experiments

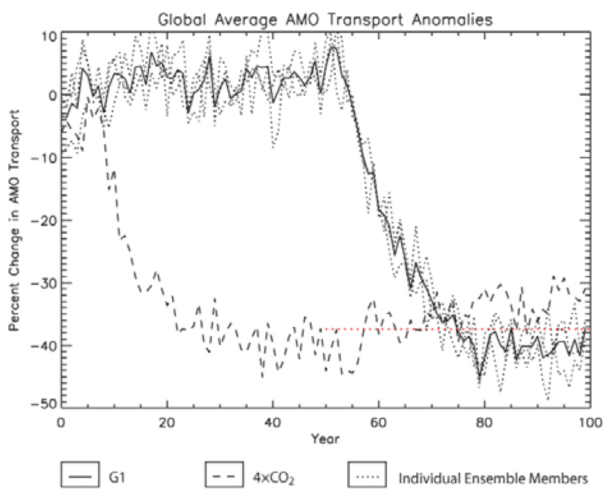

Figure 4.5: G1 AMO Transport Anomaly
Atlantic Meridional Overturning Circulation Transport [%] anomaly, G1 and 4 × CO_2 experiments

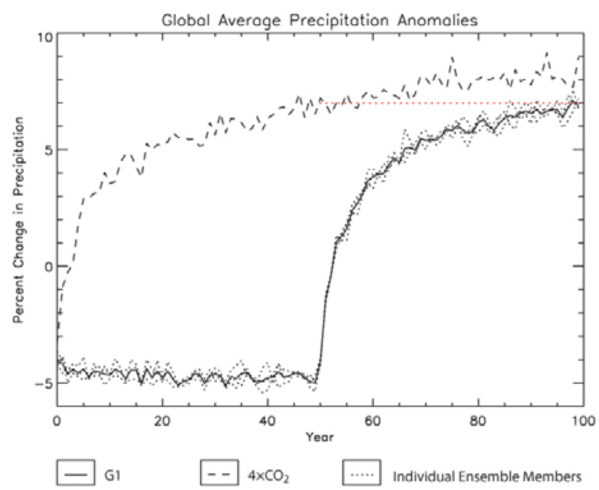

Figure 4.6: G1 Global Precipitation Anomaly
Global precipitation [%] anomaly, G1 and 4 × CO_2 experiments

The AMOC is driven by the sinking of dense, cool water in the North Atlantic Ocean. This is made dense through evaporative cooling, which both cools the water and increases its salinity. As greenhouse gas concentrations increase in the atmosphere, reductions in the air-sea temperature gradient and increased freshwater runoff to NADW formation regions are expected to decrease the AMOC (Swingdouw et al., 2005). Weak stratification below the surface layer in the North

Atlantic Deepwater (NADW) formation region prevents the dissipation of the surface salinity anomaly (here, anomalously fresh water) by transport in the condition of 4 × CO_2, but surface heat fluxes allow for a recovery of deepwater formation (Bitz et al., 2007).In the 4 × CO_2 experiment, the AMOC seems to make a slight recovery, from a roughly 40% decrease in transport toward a roughly 30% decrease in transport (relative to pre-industrial conditions). The recovery of the AMOC is a feature that has been found in earlier experiments with increased atmospheric greenhouse gas concentrations (Bitz et al., 2007; Stouffer et al., 2006; Swingdouw et al., 2005).

4.1.2 G1 RATES OF CHANGE AT TERMINATION OF GEOENGINEERING

The resulting rates of change following the failure of geoengineering are of interest, because rapid shifts in the Earth's climate can be extremely difficult for human societies and ecosystems to adapt to. The rates in **Error! Reference source not found.** were calculated over the decade after the abrupt ceasing of geoengineering, using a linear rate of change and the data from the start and endpoints of the period. During this period, the global surface temperature, ocean temperature and precipitation increased, while the AMOC and well as global sea ice volume in both hemispheres decreased. These changes to surface air temperature, precipitation, NH sea ice volume and ocean temperature are quite similar to the similar rates of change during the first decade of the instantaneous 4 × CO_2 run (Table 4-1). Notably, the rates of decrease of the AMOC and SH sea ice were larger for the geoengineering failure than they were for the 4 × CO_2 run (Table 4-1). Over the last 50 years, the rate of surface air temperature change has been 0.013°C ± 0.003°C per year[8]. For comparison, during the glacial-interglacial cycles which represent the largest global temperature changes of the past 1.000,000 years (Jansen et al., 2007), temperature varied by 4°C to 7°C over periods of 5000 years (Jansen et al., 2007), or 0.0008°C per year to 0.0014°C per year.

[8] Source: National Oceanic and Atmospheric Administration < http://www.ncdc.noaa.gov/cmb-faq/globalwarming.html>.

Table 4-1: Rates of Change of Climate Variables in G1 and 4 × CO_2 run, Post-Geoengineering						
	Surface Air Temperature [K yr^{-1}]	Ocean Temperature [K yr^{-1}]	Atlantic Meridional Overturninc Circulation [Sv yr^{-1}]	NH Sea Ice Volume [m^3 yr^{-1}]	SH Sea Ice Volume [m^3 yr^{-1}]	Precipitation [mm $month^{-1}$]
G1	0.287	0.0120	-0.284	-4.52×10^{11}	-8.32×10^{10}	0.0212
4 × CO_2	0.299	0.0114	-0.15	-4.74×10^{11}	-5.85×10^{10}	0.0200

4.1.3 G1 GEOGRAPHICAL PATTERNS, POST-GEOENGINEERING

The spatial warming pattern during the post-geoengineering period for G1 (Figure 4.7) is nearly indistinguishable from the warming pattern for the 4 × CO_2 run (Figure 3.8), owing to the fact that, following geoengineering termination, G1 is exposed to the same forcing as the 4 × CO_2 run is initially. The G1 warming pattern also bears some resemblance to the warming over the geoengineering period for the same experiment (Figure 3.6), with its polar amplification and stronger warming over land than ocean, except over the Weddell and Chuckchi Seas. However, for the G1 experiment, in the post-geoengineering period, there are no regions of cooling, warming is observed everywhere, and is strongest over the continents and high latitudes.

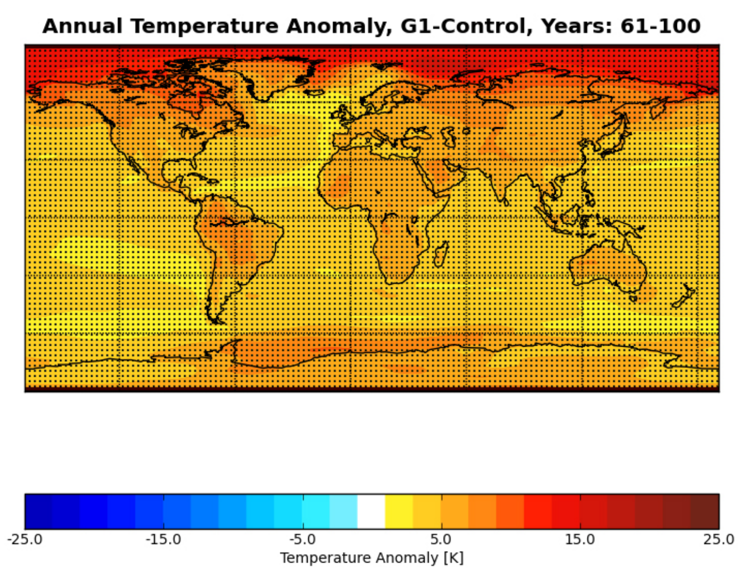

Figure 4.7: G1 Temperature Anomaly, Years 61-100

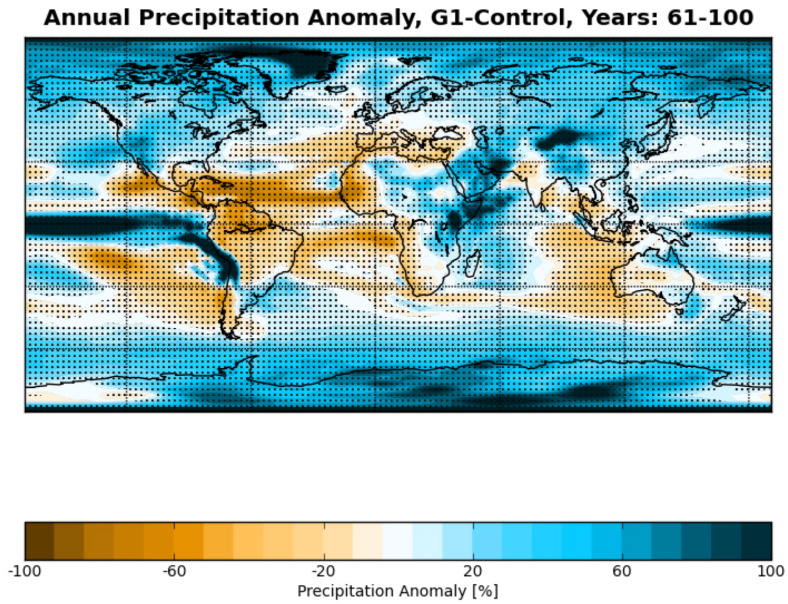

Figure 4.8: G1 Annual Percent Precipitation Anomaly, Years 61-100

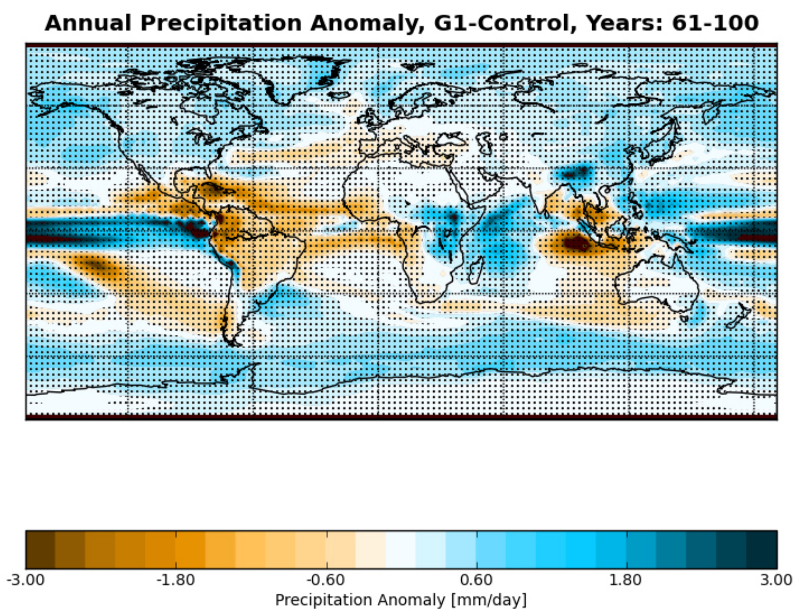

Figure 4.9: G1 Annual Absolute Precipitation Anomaly. Years 61-100

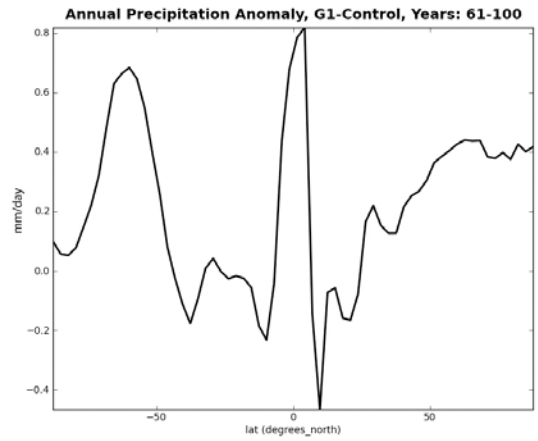

Figure 4.10: G1 Annual Zonal Precipitation Anomaly, Years 61-100

The spatial pattern of the precipitation anomaly in the G1 experiment, post-geoengineering (Figure 4.8) is likewise similar to the precipitation anomaly pattern for the 4 × CO_2 run (Figure 3.24), for the same reason as the spatial pattern for the warming. The spatial precipitation anomaly for G1 post-geoengineering also bears some resemblance to its geoengineering counterpart (Figure 3.23), with increased precipitation over the ITCZ, and drying over South America, the eastern Indian Ocean and much of the Atlantic. However, there are also marked differences: the reduction in precipitation over Asia and Europe, seen during the geoengineering period, is not present; instead, increased precipitation is found over all of these regions. A large increase in precipitation is also apparent over Greenland and a smaller overall increase in precipitation is apparent over the northern tropical and subtropical region of the Pacific Ocean.

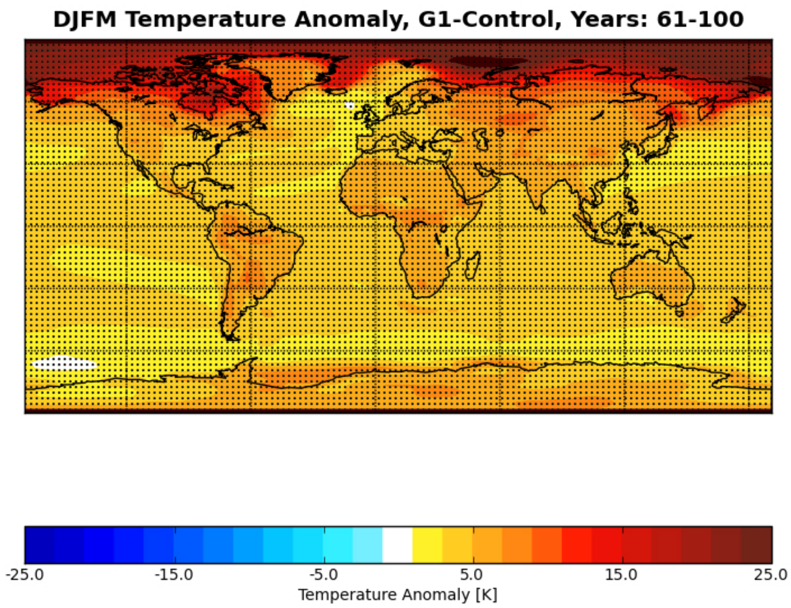

Figure 4.11: G1 DJFM Temperature Anomaly, Years 61-100

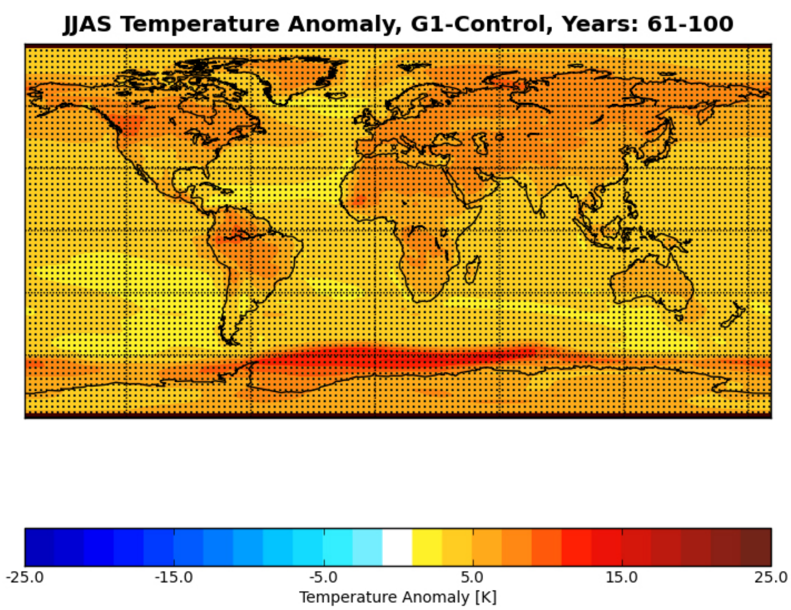

Figure 4.12: G1 JJAS Temperature Anomaly, Years 61-100

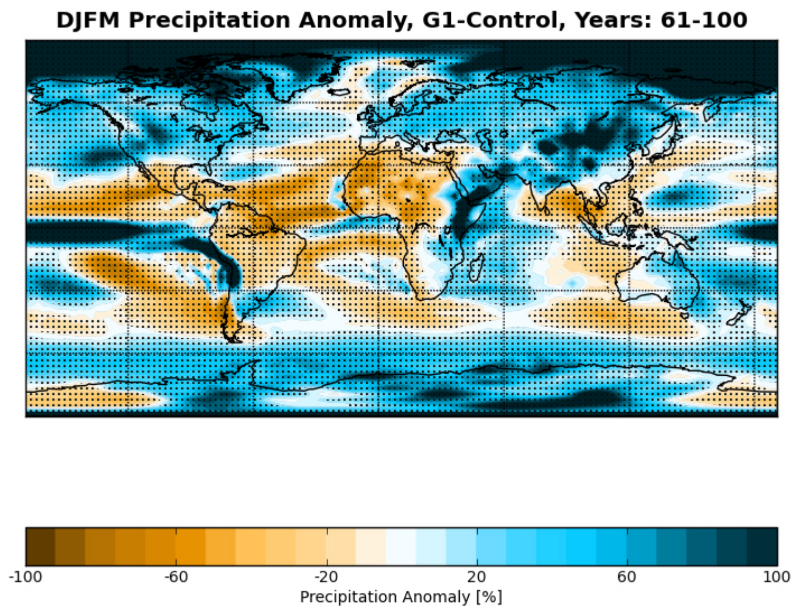

Figure 4.13: G1 DJFM Precipitation Anomaly, Years 61-100

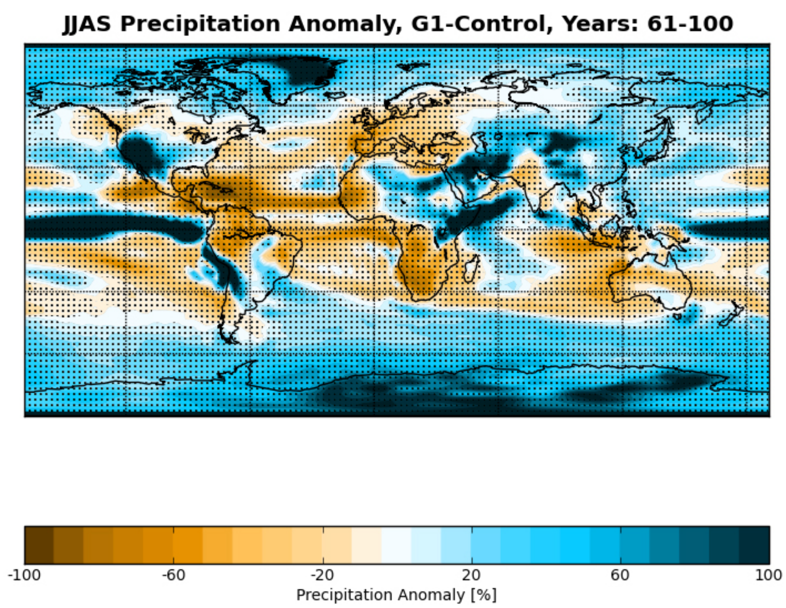

Figure 4.14: G1 JJAS Precipitation Anomaly, Years 61-100

Polar amplification of the effects of climate change is visible, especially in the Arctic, during the DJFM period which is consistent with the findings of the Fourth Assessment Report of the IPCC (Solomon, 2007). This is due to the increased CO_2 forcing, intensified by the ice and snow-albedo feedbacks, leading to the stronger surface air temperature response. Polar amplification aside, the warming is greatest over the continents ().

In the seasonal spatial plots for G1 in the post-geoengineering period (Figure 4.13 and Figure 4.14), a large increase in winter precipitation is clearly visible at and near the poles, during the DJFM period in the Arctic and during the JJAS period in the Antarctic. During the Northern Hemisphere winter, the northern half of South America experiences significant drying, as does the central Atlantic and the Southeastern Pacific. At the same time, Asia, Europe, Canada, Eastern Africa and America see increases in winter precipitation. During the JJAS period, there is some drying throughout India, most of Europe, northern South America, and both the southern tip and part of Northwestern Africa. The North Atlantic and Northeastern Pacific also experience rather strong drying. During this period, precipitation increases over the Pacific ITCZ, for reasons discussed above, and most of the northern Pacific, though some decrease in precipitation occurs over the eastern Pacific Ocean.

4.2 G2: Post-Geoengineering Period

4.2.1 G2 GLOBAL MEAN CHANGES IN KEY CLIMATE VARIABLES POST-GEOENGINEERING

In the post-geoengineering period of the G2 runs, both surface temperature (Figure 4.15) and global average precipitation (Figure 4.19) rise to meet the values of the same variables in the 1%CO_2yr^{-1} run. It should be noted with some caution that the G2 results are from a three member ensemble average of simulations, whereas the 1%CO_2yr^{-1} results are from a single run, hence the internal variability of the system for the 1%CO_2yr^{-1} is not as well-determined as for the G2 run.

Similarly to what is seen for precipitation and surface temperature, during the post-geoengineering period of the G2 run, Northern Hemisphere and Southern Hemisphere sea ice volumes approach the same values as in the 1%CO_2yr^{-1} run (Figure 4.17; Figure 4.18). As global temperatures rise, the sea ice volume decreases. As with sea ice, precipitation and surface temperature, during the post-geoengineering period of the G2 run above, AMOC transport in the G2 run also approaches the same values as in the 1%CO_2yr^{-1} run (Figure 4.20). This is again attributable to the forcing that the G2 system is exposed to post-geoengineering failure.

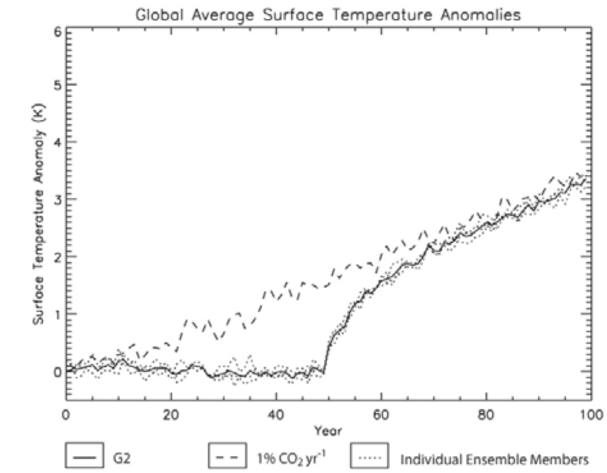

Figure 4.15: G2 Global Surface Temperature Anomaly
Global surface temperature [K] anomaly, G2 and $1\%CO_2yr^{-1}$ experiments

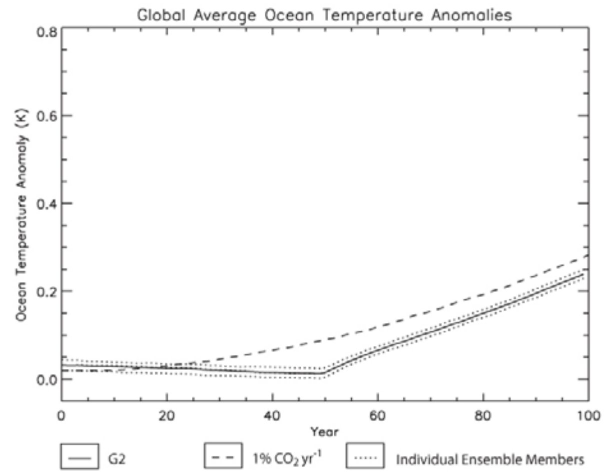

Figure 4.16: G2 Global Ocean Temperature Anomaly
Global average ocean temperature [K] anomaly, G2 and $1\%CO_2yr^{-1}$ experiments

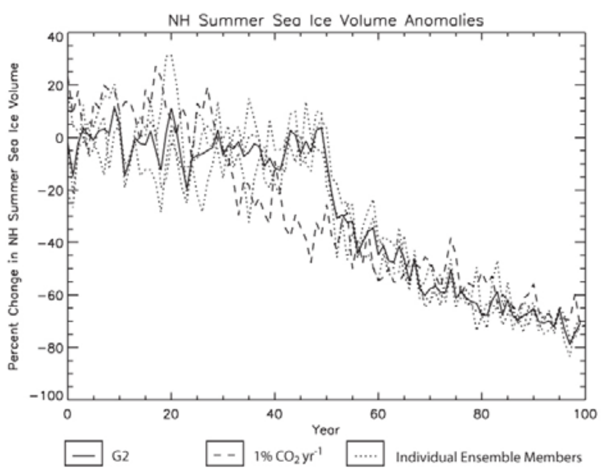

Figure 4.17: G2 NH Summer Sea Ice Volume Anomaly
NH summer sea ice volume [%] anomaly, G2 and $1\%CO_2yr^{-1}$ experiments

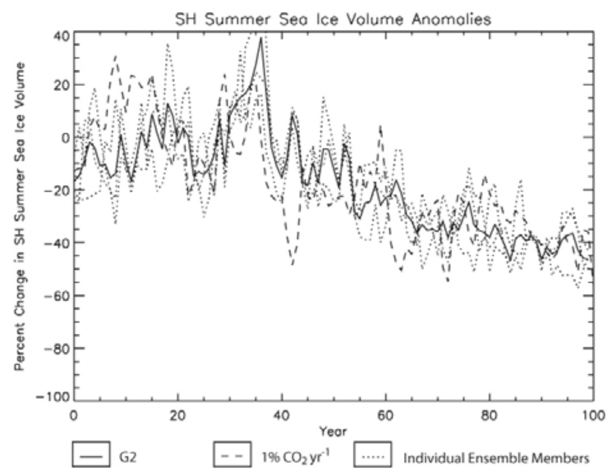

Figure 4.18: G2 SH Summer Sea Ice Volume Anomaly
SH summer sea ice volume [%] anomaly, G2 and $1\%CO_2yr^{-1}$ experiments

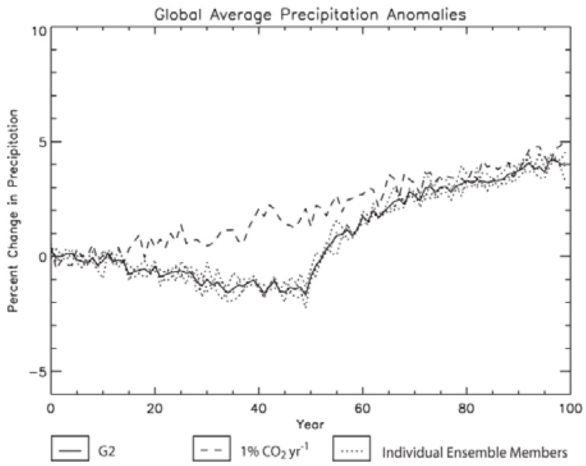

Figure 4.19: G2 Global Precipitation Anomaly
Global precipitation [%] anomaly, G2 and 1%CO_2yr^{-1} experiments

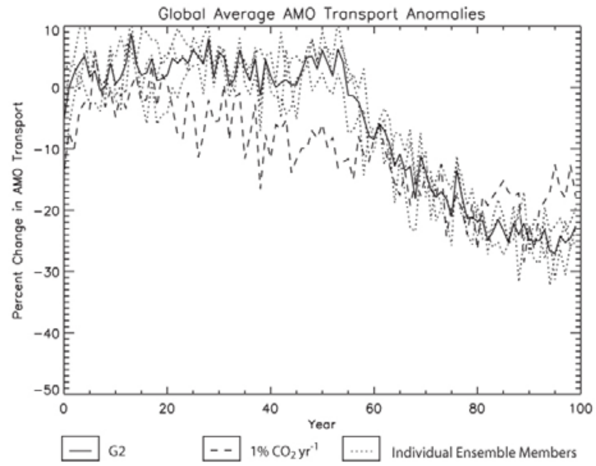

Figure 4.20: G2 AMO Transport Anomaly
Atlantic Meridional Overturning Circulation [%] anomaly, G2 and 1%CO_2yr^{-1} experiments

4.2.2 G2 RATES OF CHANGE AT TERMINATION OF GEOENGINEERING

In the decade following termination of geoengineering in the G2 run global surface temperature, average ocean temperature increased, while AMOC decreases NH sea ice volume and SH sea ice volume decreased (Table 4-2). During the first decade of the 1% increase of CO_2 yr^{-1} run, the changes in all of the variables studied were quite different than in the first decade following geoengineering termination in the G2 run, with global surface temperature, ocean temperature and precipitation increasing at a smaller rate (Table 4-2). Two variables, AMOC and SH sea ice volume, changed with opposite signs (Table 4-2), both increased in the 1% increase of CO_2 yr^{-1} run and decreased in G2. NH sea ice volume decreased in both cases, but the rate of the decrease in the first decade of the 1% increase of CO_2 yr^{-1} run was one-third that of the rate of decrease in the G2 run, following geoengineering termination (Table 4-2). The difference in rates, again, reflects the fact that, when geoengineering fails, the system for the G2 runs are immediately exposed to a greater radiative forcing than the initial forcing for the 1%CO_2yr^{-1} run.

Table 4-2: Rates of Change of Climate Variables in G2 and 1% CO_2 Year^{-1} Run, Post-Geoengineering						
	Surface Air Temperature [K yr^{-1}]	Ocean Temperature [K yr^{-1}]	Atlantic Meridional Overturninc Circulation [Sv yr^{-1}]	NH Sea Ice Volume [m^3 yr^{-1}]	SH Sea Ice Volume [m^3 yr^{-1}]	Precipitation [mm month^{-1} yr^{-1}]
G2	0.102	4.65×10^{-3}	-0.233	-2.14×10^{11}	-2.62×10^{10}	5.36×10^{-3}
1% CO_2 yr^{-1}	0.0134	2.44×10^{-5}	0.221	-4.24×10^{10}	6.28×10^{10}	1.68×10^{-3}

Though the values from the G2 post-geoengineering period are valuable as examples of how the climate system could react following the termination of a more modest geoengineering solar radiation management scheme than in the G1 experiment, values from the first decade of the 1% increase of CO_2 yr^{-1} run cannot be directly compared to those of the first decade from G2 post-geoengineering. This is because the forcings acting on the model are very different. For the 1% CO_2 yr^{-1} run, the atmospheric carbon dioxide forcing and solar constant are initially set at the preindustrial value, whereas, for G2, post-geoengineering, the model is immediately exposed to atmospheric carbon dioxide concentrations of roughly 165% of preindustrial values. Hence, the results from the G2 run post-geoengineering will be very different from those of the 1% CO_2 yr^{-1} run.

4.2.3 G2 GEOGRAPHICAL PATTERNS, POST-GEOENGINEERING

The spatial structure of the changes in precipitation and temperature (Figure 4.21; Figure 4.22) and the meridional structure of the zonal mean precipitation for G2 post-geoengineering (Figure 4.24) are very similar to G1 (Figure 4.7, Figure 4.8 and Figure 4.10), simply scaled down in magnitude. Precipitation (Figure 4.22) increases over the ITCZ, Asia, Europe, Greenland and the high latitude oceans and decreases over South America, the eastern Indian Ocean and much of the subtropical Atlantic. Surface temperature (Figure 4.21) increases everywhere and this effect is magnified over all of the continents, especially in the Northern polar region.

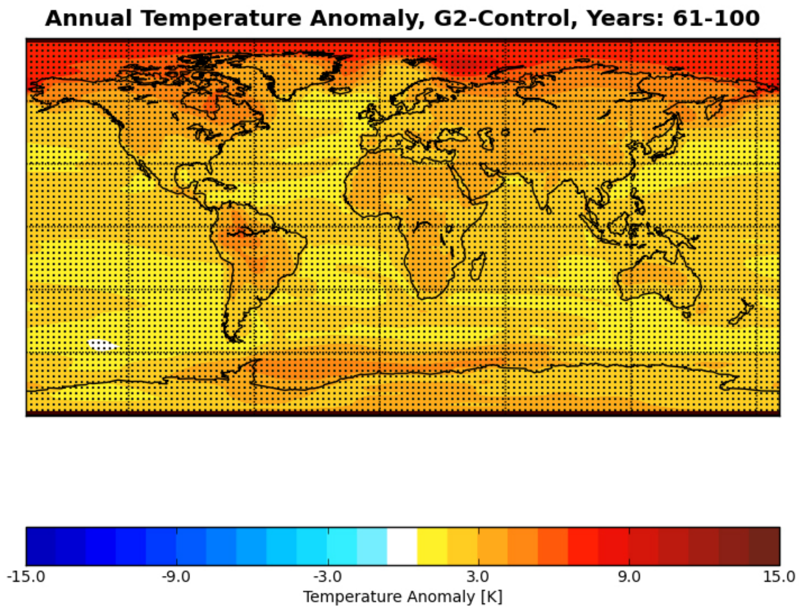

Figure 4.21: G2 Annual Temperature Anomaly, Years 61-100

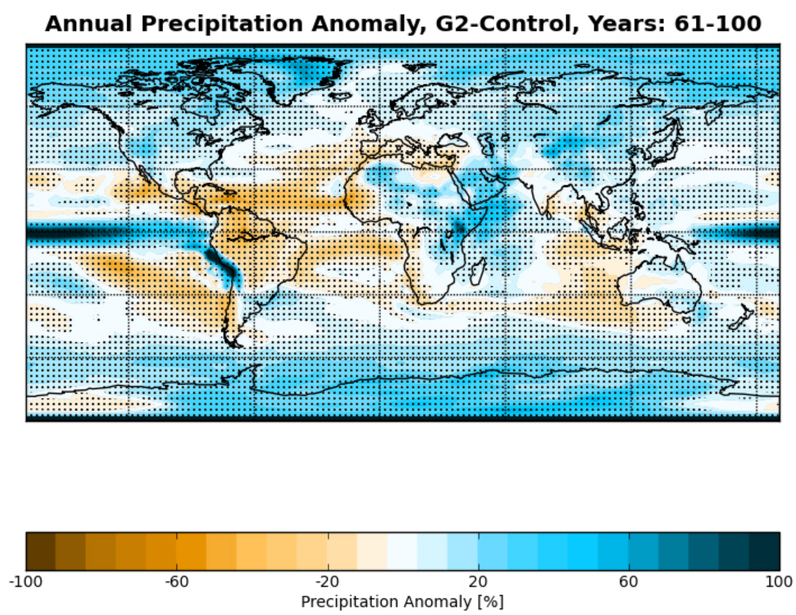

Figure 4.22: G2 Annual Percent Precipitation Anomaly, Years 61-100

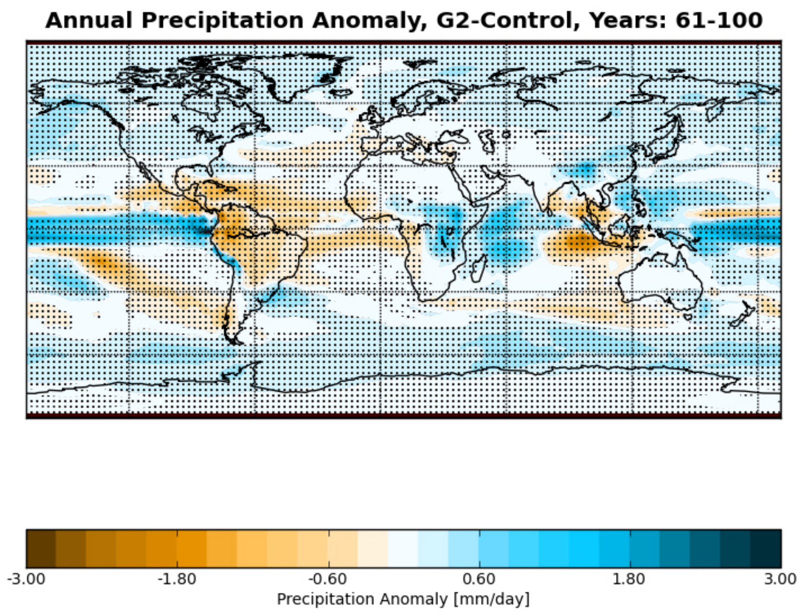

Figure 4.23: G2 Annual Absolute Precipitation Anomaly, Years 61-100

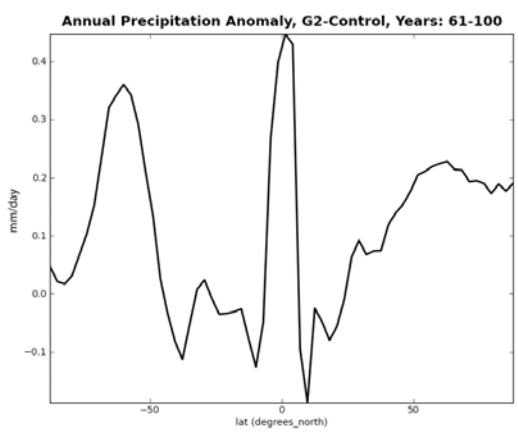

Figure 4.24: Zonal Annual Precipitation Anomaly, G2-Control, Years 61-100

In the G2 post-geoengineering period (Figure 4.25), the warming during the DJFM season is most pronounced in the northern high latitude regions and over continents, though warming is seen, during both the DJFM and JJAS (Figure 4.26) periods, essentially everywhere. During the DJFM period precipitation (Figure 4.27) increases over northern high latitude regions, including the Arctic and during the JJAS period (Figure 4.28), precipitation increases in the high latitudes, particularly in the Antarctic. As with the G1 experiment post-geoengineering, during the Northern Hemisphere winter, most of Africa, the northern half of South America and the subtropical Atlantic experience significant decreases in precipitation, while increases in precipitation are evident over Asia, Europe, Canada, Eastern Africa, most of North America and the ITCZ of the Pacific Ocean. As with the G1 experiment post-geoengineering, during the JJAS period, there is a reduction in precipitation over Europe, northern South America, the southern tip of Africa and most of the subtropical and midlatitude Atlantic.

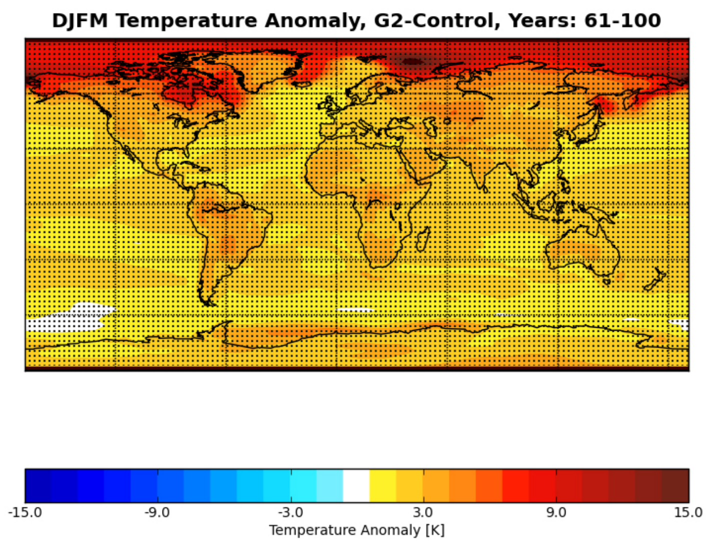

Figure 4.25: G2 DJFM Temperature Anomaly, Years 61-100

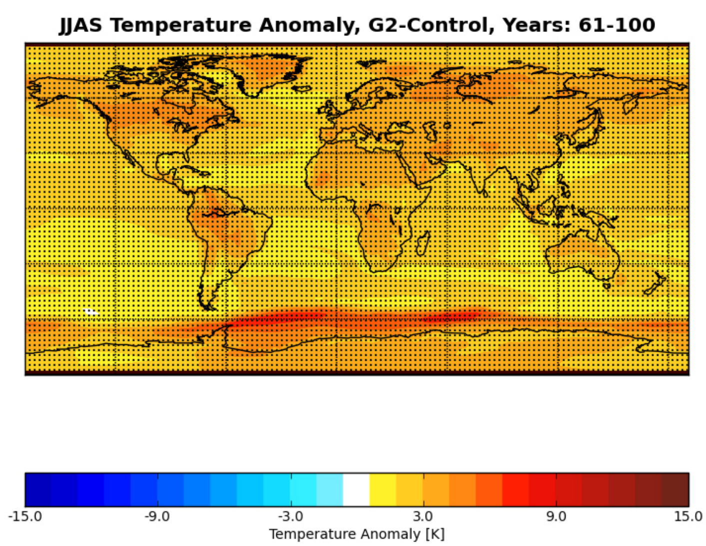

Figure 4.26: G2 JJAS Temperature Anomaly, Years 61-100

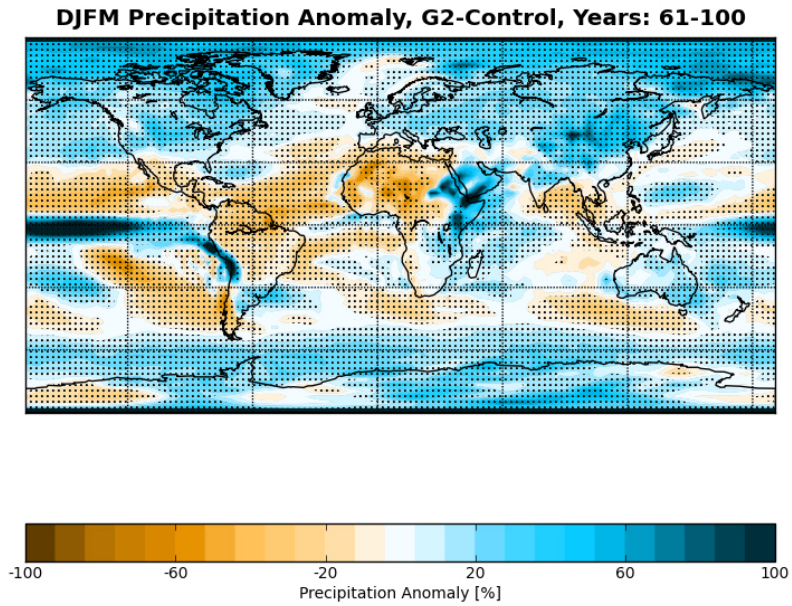

Figure 4.27: G2 DJFM Percent Precipitation Anomaly, Years 61-100

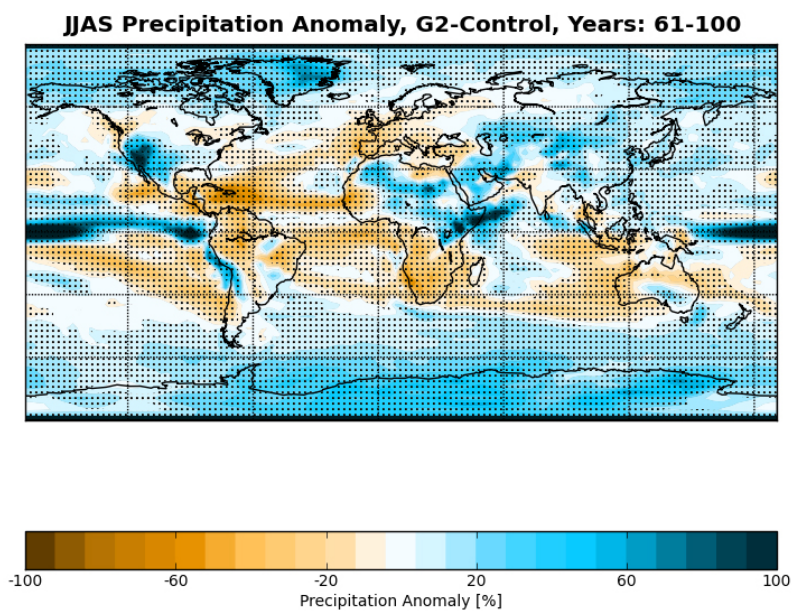

Figure 4.28: G2 JJAS Percent Precipitation Anomaly, Years 61-100

5 Conclusions

The results presented here, from the GeoMIP G1 and G2 experiments, support earlier results which showed that geoengineering schemes which involve a reduction in the solar constant, can prevent an increase in mean global surface temperature as atmospheric carbon dioxide concentrations increase, even offsetting the forcing of quadrupled atmospheric carbon dioxide concentrations in the G1 experiment. However, owing to the latitudinally varying effects of the two forcings, zonal temperature changes do occur even while the mean global surface temperature remains constant, with high latitude warming being offset by a cooling in the tropical and subtropical regions. The G2 experiment was very similar to the G1 experiment in terms of the spatial surface temperature changes, though the anomalies seen in the G2 experiment are of more limited size and the regions of statistical significance are smaller.

During the geoengineering period, a statistically significant decrease in global precipitation, particularly over the ocean, was apparent in the G1 run, as were some important seasonal changes. Notable among these was a reduction in precipitation over South Asia during the monsoon season (JJAS). As with temperature, the pattern of precipitation change during the geoengineering period for G2 is similar to the same period in G1, albeit reduced in magnitude. However, most of the spatial precipitation change seen in G2 fails to be statistically significant.

Following the termination of geoengineering, the G1 experiment responds rapidly, with surface and ocean temperatures, NH and SH summer sea ice volume, AMOC transport volume and global precipitation reaching the same values found in the $4 \times CO_2$ experiment's first 10 years. Following geoengineering failure, the G2 run also experiences rapid climate change, but does not approach that seen after the first 10 years of the $1\%CO_2yr^{-1}$ experiment, because the atmospheric CO_2 concentrations are quite different in the two runs.

The findings of this experiment present two ethical issues for the proponent of deploying geoengineering: (1) that spatial effects are unequally distributed and hence, raise issues of compensation for those who would be affected by such a scheme and, (2) that the hazard of rapid climate change following geoengineering failure, as seen in the two experiments performed here, and any potential harms that it could cause must be weighed in any potential proposal for deployment. These results therefore support two of Alan Robock's arguments against the deployment of stratospheric sulfate aerosol geoengineering: (1) because the effects of geoengineering are unequally distributed, a geopolitical concern regarding who gets to decide what the ideal climate emerges and (2) there are potentially dangerous consequences to geoengineering, both in terms of disruptions to the Earth's hydrological cycle and in terms of rapid changes to the Earth's climate should geoengineering be terminated for whatever reason.

Neither G1 nor G2 represent actual geoengineering proposals. However, the problems which they present, in terms of spatial variation of climate change and the climatic effect of the sudden termination of geoengineering in the presence of increased atmospheric greenhouse gas concentrations on the Earth's climate, are issues that any solar radiation management geoengineering proposal must address. Though both the G1 and G2 experiments undergo geoengineering termination with atmospheric carbon dioxide concentrations greater than current atmospheric concentrations, the rapid rates of warming that occur following this termination in both experiments are a potential cause for concern. Given that the rate of the current warming is already too rapid for many ecosystems to adjust (IPCC 2007), potentially greater rates of change from geoengineering termination are a serious issue for solar radiation management geoengineering schemes, including those using atmospheric aerosols.

Assuming an ethical obligation to the well-being of future generations, the results in this thesis also support Gardiner's objection, that because any sort of climate catastrophe is not upon the present generation, there may be better ways to prepare or more owed to future generations than stratospheric sulfate aerosol geoengineering.

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