Regional Climate Responses to Geoengineering with Tropical and Arctic SO_2 Injections

Alan Robock[1], Luke Oman[2], and Georgiy L. Stenchikov[1]

[1]Department of Environmental Sciences, Rutgers University, New Brunswick, New Jersey

[2]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland

March, 2008

Revised May, 2008

Journal of Geophysical Research, in press

Corresponding Author:
Alan Robock
Department of Environmental Sciences
Rutgers University
14 College Farm Road
New Brunswick, NJ 08901
Phone: 732-932-9800, x6222
Fax: 732-932-8644
E-mail: robock@envsci.rutgers.edu

Abstract

Anthropogenic stratospheric aerosol production, so as to reduce solar insolation and cool Earth, has been suggested as an emergency response to geoengineer the planet in response to global warming. While volcanic eruptions have been suggested as innocuous examples of stratospheric aerosols cooling the planet, the volcano analog actually argues against geoengineering because of ozone depletion and regional hydrologic and temperature responses. To further investigate the climate response, here we simulate the climate response to both tropical and Arctic stratospheric injection of sulfate aerosol precursors using a comprehensive atmosphere-ocean general circulation model, the National Aeronautics and Space Administration Goddard Institute for Space Studies ModelE. We inject SO_2 and the model converts it to sulfate aerosols, transports the aerosols and removes them through dry and wet deposition, and calculates the climate response to the radiative forcing from the aerosols. We conduct simulations of future climate with the Intergovernmental Panel on Climate Change A1B business-as-usual scenario both with and without geoengineering, and compare the results. We find that if there were a way to continuously inject SO_2 into the lower stratosphere, it would produce global cooling. Tropical SO_2 injection would produce sustained cooling over most of the world, with more cooling over continents. Arctic SO_2 injection would not just cool the Arctic. Both tropical and Arctic SO_2 injection would disrupt the Asian and African summer monsoons, reducing precipitation to the food supply for billions of people. These regional climate anomalies are but one of many reasons that argue against the implementation of this kind of geoengineering.

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992. Signed by 194 countries and ratified by 189, including the United States, it came into force in 1994. It says in part, “The ultimate objective of this Convention ... is to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” “Dangerous anthropogenic interference” was not defined, but is now generally considered to be at a CO_2 level of about 450 ppm, and we are currently at about 385 ppm.

In light of the failure of society to take any concerted actions to deal with global warming in spite of the 1992 UNFCCC agreement, two prominent atmospheric scientists published papers recently suggesting that society consider geoengineering solutions to global warming [*Crutzen*, 2006; *Wigley*, 2006]. While this suggestion is not new [*Rusin and Flit*, 1960; *Environmental Pollution Panel*, 1965; *Budyko*, 1977; *Cicerone et al.*, 1992; *Panel on Policy Implications of Greenhouse Warming*, 1992; *Leemans et al.*, 1996; *Dickinson*, 1996; *Schneider*, 1996, 2001; *Flannery et al.*, 1997; *Teller et al.*, 1997, 1999, 2002; *Keith*, 2000, 2001; *Boyd et al.*, 2000; *Khan et al.*, 2001; *Bower et al.*, 2006; and a long history of geoengineering proposals as detailed by *Fleming*, 2004, 2006], it generated much interest in the press and in the scientific community, including five commentaries published with the *Crutzen* [2006] article: *MacCracken* [2006], *Bengtsson* [2006], *Cicerone* [2006], *Kiehl* [2006], and *Lawrence* [2006].

There have been many types of suggested geoengineering, including those based on changing the CO_2 concentration in the atmosphere (ocean fertilization, carbon capture and sequestration, and genetic modification of ecosystem productivity), damming the ocean (e.g., Gibraltar or Bering Straits), modification of the ocean surface albedo or evaporation, or albedo enhancement of marine stratocumulus clouds (see references above). Another approach, evaluated in this paper, is reducing the incoming solar radiation with artificial stratospheric aerosols or space-based sun shields, that is, injecting sulfate or soot aerosols or their precursors into the stratosphere or by placing mirrors or shades in orbit between the Sun and Earth to reduce the amount of insolation [*Angel*, 2006]. In the case of “solar radiation management” [*Lane et al.*, 2007], the idea is that reduced insolation will compensate for the additional radiative forcing from greenhouse gases. As *Teller et al.* [1997] point out, “The Earth’s surface is not considered for reasons of land-use and local microclimate impacts, while the ocean surface poses stability/durability/navigation compatibility concerns, and tropospheric residence times are not usefully long for the types of scattering systems which we consider.”

This paper evaluates the suggestions for using sulfate aerosols in the stratosphere to reduce insolation. These ideas have been evaluated with simple general circulation model (GCM) experiments by *Govindasamy and Caldeira* [2000], in which geoengineering was simulated as a reduction of the solar constant. However, the details of the solar forcing from the specific effects of stratospheric aerosols were not evaluated in any detail. *Govindasamy and Caldeira* [2000] used a slab ocean and only evaluated equilibrium experiments that reduced the solar constant at the same time as doubling CO_2. They found that a reduction of 1.8% in solar irradiance would balance the global warming produced by a CO_2 doubling. *Govindasamy et al.* [2002] evaluated the effects of the same experiment on land surface vegetation and the carbon cycle with the same GCM coupled to a terrestrial biosphere model, but again did not evaluate the effects of aerosols. *Govindasamy et al.* [2003] continued the analysis for a quadrupling of CO_2, but again with equilibrium experiments and a slab ocean.

Teller et al. [1997] discussed various geoengineering proposals, and *Teller et al.* [1999, 2002] did not propose new geoengineering beyond *Teller et al.* [1997], but described the results of the *Govindasamy and Caldeira* [2000] and *Govindasamy et al.* [2002] GCM experiments.

Wigley [2006], with an energy balance model, and *Matthews and Caldeira* [2007], with an intermediate complexity atmosphere-ocean GCM coupled to a carbon cycle model, used solar constant reduction to mimic geoengineering. The only experiment done so far explicitly looking at stratospheric aerosol injection was by *Rasch et al.* [2008] with an atmospheric GCM coupled to a slab ocean, who used tropical injection of stratospheric aerosols prescribed at two size distributions. Most of the previous experiments looked at the equilibrium climate response; the only time-dependent studies were by *Wigley* [2006] with an energy-balance model and *Matthews and Caldeira* [2007] with a simplified GCM. The results presented here are the first with a comprehensive atmosphere-ocean GCM, the first to include interactive injection, transport, and removal of stratospheric aerosol for Arctic injection, and the first comprehensive GCM experiment to look at the time-dependent climate system response.

2. Volcanic eruptions as an analog for geoengineering

Geoengineering suggestions [e.g., *Crutzen*, 2006; *Wigley*, 2006] have claimed that volcanic eruptions provide a good analog for stratospheric aerosol injection, and that the example of the 1991 Mt. Pinatubo eruption was a rather innocuous event, which should give us confidence that geoengineering is safe. However, tropical eruptions produce changes in atmospheric circulation, with winter warming over Northern Hemisphere continents [e.g., *Graf et al.*, 1993; *Kodera et al.*, 1996; *Robock*, 2000; *Stenchikov et al.*, 2002, 2004, 2006], but this winter warming is only for one or two years after the eruption, when a temperature gradient is maintained in the stratosphere and also depends on the phase of the quasi-biennial oscillation [*Stenchikov et al.*, 2004]. Here we address the question of whether such a circulation anomaly would persist with a continuous aerosol cloud. If so, regional warming from greenhouse gases would be enhanced over some regions by a geoengineering “solution.” Furthermore, high latitude eruptions weaken the Asian and African monsoons causing precipitation reductions

[*Oman et al.*, 2005, 2006a]. In fact, the 1783-1784 Laki eruption produced famine in Africa, India, and Japan. Here we examine how smaller amounts of stratospheric aerosols would affect summer wind and precipitation patterns and investigate whether schemes to geoengineer just the Arctic would be confined there.

Robock and Liu [1994], using model simulations of volcanic eruptions, and *Trenberth and Dai* [2007], using observations following the 1991 Pinatubo eruption, found large reductions in the strength of the global hydrological cycle including in precipitation, soil moisture, and river flow. Here we also examine the hydrological response to a long-lasting stratospheric aerosol cloud to see whether this response was due to the episodic and unbalanced nature of the aerosol forcing, or is a robust response to geoengineering.

Volcanic eruptions have also been observed to produce large stratospheric ozone depletion following the 1982 El Chichón and 1991 Pinatubo eruptions [*Solomon*, 1999]. *Tilmes et al.* [2008] showed that, in spite of the gradual decline of anthropogenic ozone depleting substances expected over the next several decades, geoengineering with stratospheric aerosols would produce large ozone depletion in the Arctic in winters with a cold polar lower stratosphere, and would delay the disappearance of the Antarctic ozone hole, with effects lasting throughout the 21st Century.

Thus, on first glance, the volcano analog actually seems to argue against geoengineering, as there are negative consequences that accompany the cooling [*Robock*, 2008a]. Here we evaluate the regional climate changes in detail to see the climatic response to both tropical and Arctic aerosol precursor injection.

3. Experimental Design

A number of different aerosol types have been proposed for geoengineering. *Budyko* [1977] describes detailed plans for adjusting the sulfur content of jet fuel so that airplanes traveling in the lower stratosphere would inject the correct amount (as determined from climate model calculations) of SO_2 into the stratosphere to form sulfate aerosols. *Turco* [1995] proposed a scheme involving the conversion and release of fossil fuel sulfur as carbonyl sulfide (OCS), which enhances the stratospheric sulfate layer, discussing the processes and potential pitfalls. *Leemans et al.* [1996] discussed many options, and pointed out that sulfate aerosols in the stratosphere might deplete ozone, and that pure soot aerosols, while not chemically reactive with ozone, would affect ozone chemistry and reduce ozone due to the ensuing temperature rise in the stratosphere. This was verified in GCM calculations by *Mills et al.* [2008] recently. *Teller et al.* [1997] suggested using dielectric material of an optimum size, electrical conductors (metal particles), or resonant molecules to scatter sunlight. They claimed that "appropriately fine-scale particulate loadings of the middle stratosphere will persist for five-year intervals" which seems like an overestimate to us, based on past work with volcanic sulfate aerosols, which have a 1-year e-folding lifetime [e.g., *Stenchikov et al.*, 1998; *Gao et al.*, 2007]. *Budyko* [1977] assumed an average lifetime of stratospheric aerosols of two years, which is a more reasonable estimate.

Teller et al. [1997] claimed that "Consistent with the slow latitudinal mixing-time of the stratosphere well above the tropopause, different amounts of scattering material might be deployed (e.g., at middle stratospheric altitudes, ~25 km) at different latitudes, so as to vary the magnitude of insolation modulation for relatively narrow latitudinal bands around the Earth, e.g., to reduce heating of the tropics by preferential loading of the mid-stratospheric tropical reservoir with insolation scatterer," but based on observations of the dispersion of stratospheric volcanic aerosols, this claim does not describe the way the stratosphere behaves. In fact, proposals to inject artificial aerosols into the tropical stratosphere, so that atmospheric winds would disperse them globally, earlier in the same paper are more consistent with stratospheric dynamics. As *Budyko* [1977] says, "The choice of the region where the reagent is scattered is of limited importance since data on the dispersion of product of volcanic eruptions demonstrate that reagent from any point outside the tropical zone rapidly spreads over the entire hemisphere." But he also continues, "Circulation in the lower stratosphere can be of importance in selecting optimal regions and periods of time for ejecting the reagent to ensure its most effective use."

Previous geoengineering simulations have introduced sulfate aerosol precursors into the tropical stratosphere [*Rasch et al.*, 2008] or simulated aerosol injection by reducing solar insolation either uniformly globally [*Govindasamy and Caldeira*, 2000; *Govindasamy et al.*, 2002, 2003; *Matthews and Caldeira*, 2007] or in the Arctic [*Lane et al.*, 2007]. Therefore, we decided to conduct experiments for both tropical and Arctic SO_2 injections, and to calculate the time-dependent climate response.

We use the National Aeronautics and Space Administration Goddard Institute for Space Studies ModelE atmosphere-ocean GCM. We used the stratospheric version with 4° latitude by 5° longitude horizontal resolution and 23 vertical levels up to 80 km [*Schmidt et al*., 2006]. It is fully coupled to a 4° latitude by 5° longitude dynamic ocean with 13 vertical levels [*Russell et al*., 1995]. It is important to use a full dynamic ocean in these simulations to obtain the most realistic climate response, including how long it takes for the temperature and precipitation to recover if the injecting of SO_2 should stop. This climate model has been tested extensively in global warming experiments [*Hansen et al.*, 2005; *Schmidt et al.*, 2006] and to examine the effects of volcanic eruptions on climate [*Oman et al.*, 2005, 2006a, 2006b] and nuclear winter [*Robock et al.*, 2007a, 2007b]. The climate model (with a mixed-layer ocean) does an excellent job of modeling the climatic response to the 1783 Laki [*Oman et al.*, 2006a] and the 1912 Katmai [*Oman et al.*, 2005] volcanic eruptions. We have also used this model to simulate the transport and removal of sulfate aerosols from tropical and high-latitude volcanic eruptions [*Oman et al*., 2006b], and have shown that it does a good job of simulating the lifetime and distribution of the volcanic aerosols. In the stratosphere, the aerosols from a tropical eruption have an e-folding residence time of 12 months in the model, in excellent agreement with observations, although the model transports aerosols poleward a little too fast.

The aerosol module [*Koch et al.*, 2006] accounts for SO_2 conversion to sulfate aerosols, and transport and removal of the aerosols. The radiative forcing from the aerosols is fully interactive with the atmospheric circulation. We define the dry aerosol effective radius as 0.25 μm, compared to 0.35 μm for our Pinatubo simulations. This creates hydrated sulfate aerosols with an effective radius of approximately 0.30-0.35 μm for our geoengineering runs and 0.47-0.52 μm for our Pinatubo simulations. It is difficult to say the size to which the aerosols will grow without a microphysical model that has coagulation, but by injecting SO_2 continuously (as compared to one eruption per year), coagulation would be reduced, since concentrations would be lower and the aerosol particles will be more globally distributed. The smaller size aerosols have a slightly longer lifetime so this would reduce the rate of injection needed to maintain a specific loading, as described in detail by *Rasch et al.* [2008]. By using a smaller aerosol size (about 30% less than Pinatubo), there is about half the heating of the lower tropical stratosphere (0.2-0.5°C for our 5 Tg/yr case) as compared to the equivalent loading using a Pinatubo size aerosol. But as *Tilmes et al.* [2008] point out, smaller aerosol particles would cause much more ozone depletion for the same mass of aerosol, because they would have a larger total surface area for chemical reactions. For our tropical experiments, we injected SO_2 at a slightly lower altitude than Pinatubo. The altitude and size distribution of the aerosols affect the amount of warming of the tropopause cold point and the amount of additional water vapor let into the stratosphere, which produces global warming to counteract the geoengineering. Our model includes this feedback, but we have not yet examined the sensitivity of the results to the details for stratospheric injection height and size distribution.

It is possible to conduct experiments gradually increasing geoengineering to just match global warming and keep global average surface air temperature constant [*Wigley*, 2006], but this presupposes that the current climate (whenever geoengineering would start) would be the optimal one. As we were interested in the response of the climate system to a “permanent” stratospheric aerosol cloud, we conducted experiments by injection of SO_2 at a constant rate for 20 years, and then continuing our experiments for another 20 years to examine the response to an instantaneous shut-off of geoengineering. We conducted the following GCM simulations:

- 80-yr control run with greenhouse concentrations and tropospheric aerosols at 1999 levels.
- 40-yr run forced by greenhouse gases (CO_2, CH_4, N_2O, O_3) and tropospheric aerosols (sulfate, biogenic, and soot), using the IPCC A1B business-as-usual global warming scenario. We conducted a 3-member ensemble with different initial conditions for each ensemble member to address the issue of random climate variability. We will refer to this as the A1B run.
- 40-yr A1B anthropogenic forcing plus Arctic lower stratospheric injection of 3 Mt SO_2/yr, also a 3-member ensemble (Arctic 3 Mt/yr run).
- 40-yr A1B anthropogenic forcing plus tropical lower stratospheric injection of 5 Mt SO_2/yr, also a 3-member ensemble (Tropical 5 Mt/yr run).
- 40-yr A1B anthropogenic forcing plus tropical lower stratospheric injection of 10 Mt SO_2/yr, only one run (Tropical 10 Mt/yr run).

We only conducted one Tropical 10 Mt/yr run because it is an extreme case and the variability between ensemble members is small. We focus most of the analysis on the Arctic 3 Mt/yr and Tropical 5 Mt/yr runs. For the tropical experiments, we put SO_2 into a box one grid cell wide and three model layers thick over the Equator at longitude 120°E in the lower stratosphere (16-23 km) at every time step at a rate equal to 5 Mt/yr or 10 Mt/yr for 20 years, and then continue to run for another 20 years to see how fast the system warms afterwards. As the 1991 Mt. Pinatubo eruption put about 20 Mt of SO_2 into the stratosphere [*Bluth et al.*, 1992], 5 Mt/yr is the equivalent of a Pinatubo eruption every 4 years and 10 Mt/yr is a Pinatubo every 2 years, but we inject the SO_2 continuously at those rates in the experiments here. For the Arctic experiment, we used a lower injection rate, as the idea is to limit the climate response to the Arctic and produce a shorter lifetime for the aerosols. We injected SO_2 continuously at a rate equal to 3 Mt/yr into a box one grid cell wide and three model layers thick at latitude 68°N and longitude 120°E in the lower stratosphere (10-15 km). (The longitude of the injection is arbitrary and does not affect the results, as the atmosphere quickly smoothes out the aerosol distribution.)

We should also point out that we know of no practical mechanism for actually injecting SO_2 into the stratosphere, on a continuous or even episodic basis, at the rates in our experiments. Suggestions of a geoengineering air force, sulfur injection from commercial air flights, artillery, and hoses suspended from dirigibles are all problematic, but discussion of the details is beyond the scope of this paper. Nevertheless, because there have been serious suggestions to attempt to develop such technology, we study here the climate response to hypothetical SO_2 injections.

4. Results

Figure 1 shows the annual average surface air temperature for the ensemble mean of each of our runs compared to the observed climate change since 1880. While the A1B simulation produces continued global warming at a rate very similar to that observed for the past 30 yr, each of the geoengineering runs reduces the global warming, with more reduction for more SO_2 injected. However, the Arctic SO_2 has a proportionately smaller impact on cooling the climate for two reasons. The lifetime of the aerosols is shorter, as they are removed mainly in the Arctic, due to the prevailing stratospheric circulation, while the tropical aerosols are transported poleward before much removal. In addition, because the Arctic aerosols are at high latitudes, they cover a relatively small area and the intensity of solar radiation is less there. While the mid-summer insolation is the same at high latitudes as at lower latitudes, averaged over the year, there is less radiation to scatter. The global average reduction in downward shortwave radiation at the surface for the Arctic 3 Mt/yr is only about 0.2 W m^{-2}, while for the Tropical 5 Mt/yr run it is 1.8 W m^{-2} (Figure 2). The effects of the Tropical 10 Mt/yr case are approximately double those of the Tropical 5 Mt/yr case, so we concentrate on the latter for detailed analysis of a Tropical scenario. Infrared effects of the aerosols (on enhanced downward radiation) are 2 orders of magnitude less than shortwave effects.

Figure 2 also shows the global average temperature and precipitation anomalies for the A1B, Arctic 3 Mt/yr, and Tropical 5 Mt/yr runs. The global average precipitation is reduced along with the temperature in the geoengineering runs, as expected. However, compared to the radiative forcing from greenhouse gases, the radiative forcing from reduction of solar radiation has a disproportionately large impact on precipitation as compared to temperature, because the radiative forcing from shortwave radiation has no compensating impact on the vertical temperature structure of the atmosphere [*Yang et al.*, 2003]. This can be seen, for example, by comparing years 15-20 for the A1B and Tropical 5 Mt/yr runs. While the temperature changes are about the same (+0.4°C for the warming and –0.4°C for the cooling), the precipitation reduction for the Tropical 5 Mt/yr run is almost twice the precipitation increase for the A1B run. In fact, for a 1 W m^{-2} change in radiative forcing in the shortwave, we get a 1.7% change in precipitation, but for the same change in the longwave, we get 1.0%.

We now examine the seasonal and regional distributions of radiative forcing and climate change. We examine a 10-year average of the anomaly patterns for the second half of the 20-yr period during which we applied the geoengineering forcing, by which time any initial effects from the initiation of geoengineering are minimal (Figure 1). Figure 3 shows the change in downward surface shortwave flux from the Tropical 5 Mt/yr and Arctic 3 Mt/yr runs. The Arctic aerosol precursors were emitted at 68°N, and the aerosols spread both northward and southward. Although the main radiative forcing is in the Arctic, the effect is significant as far south as 30°N. Thus suggestions of geoengineering only the Arctic, as simulated in preliminary experiments by reducing the incoming solar radiation in Arctic caps with fixed southern borders [*Lane et al.*, 2007], are not supported by these results. The radiative forcing from the Tropical 5 Mt injection is rather uniform, as the aerosols spread poleward before being removed. The pattern is quite similar to what would be achieved from a uniform reduction of insolation. The e-folding lifetime of the stratospheric aerosols for the Arctic 3 Mt/yr case is 3 months, while for the Tropical 5 Mt/yr case it is 12 months, comparable to that for volcanic eruptions. There is a clear seasonal cycle in the e-folding lifetime of the stratospheric aerosols in the Arctic case ranging from 2 to 4 months. The maximum lifetime occurs during boreal summer with a minimum during boreal winter with the formation of the polar vortex and higher rates of tropopause folding.

The surface air temperature and precipitation changes for the A1B runs as compared to the mean of the control run are shown in Figure 4. As is typical of such results, the warming is enhanced in the polar regions, particularly in the winter. There is less warming in the northeast Atlantic Ocean and around Antarctica because of ocean circulation feedbacks. Annual average changes in precipitation are very small in spite of the warming, as expected [*Yang et al.*, 2003]. There are no significant precipitation changes over land in Northern Hemisphere summer or winter either.

While the Arctic 3 Mt/yr scenario produces only a little less global-average warming than the A1B run (Figures 2-3), there are still large regional changes (Figure 5). The Northern Hemisphere warms less than in the A1B run (Figure 5, right column), but there is even more warming over northern Africa and India in the Northern Hemisphere summer. This is produced by a weakening of the African and Asian summer monsoon circulation, an effect found previously from high latitude volcanic eruptions, both in model results and in observations [*Oman et al.*, 2005, 2006a] and in nuclear winter simulations [*Robock et al.*, 2007a, 2007b]. The warming is produced by a reduction in cloudiness. And even though the annual average temperature does not change much anywhere, there is still a small warming over eastern Europe (Figure 5, top left panel), particularly in the Northern Hemisphere summer (Figure 5, middle left panel). The winter warming in the Bering Sea (Figure 5, lower left panel), is from a strengthened Aleutian Low advecting warmer maritime air to the north, although it is difficult to gauge its significance. The temperature field is close to significant at the 5% level, but the sea level pressure change, 1.0-1.5 mb lower than the control over this time period, is not significant.

Figure 6 shows the temperature changes for the Tropical 5 Mt/yr case. As compared to the A1B case (right column), there is global cooling, particularly over the continents, as expected. Even in absolute terms as compared to the control case (left column), there is cooling. But even in this case, there is a region of warming over India in the summer, for the same reasons as discussed above. In the Tropical 5 Mt/yr case there is more cooling over the Asian continent than in the Arctic 3 Mt/yr case (Figure 5), but because the aerosol cloud also covers the tropics it also cools the ocean. Therefore, the effect on the temperature gradient is not as large and there is not as large an impact on the summer monsoon.

The Northern Hemisphere winter pattern for the Tropical 5 Mt/yr case (Figure 6, bottom row) shows little evidence of winter warming, which is found in the first, and sometimes second, winter after tropical volcanic eruptions, as discussed above. The winter warming pattern, the positive mode of the Arctic Oscillation [*Thompson and Wallace*, 1998], is produced by a temperature gradient in the lower stratosphere caused by heating of the tropical region by absorption of both terrestrial longwave and solar near-infrared radiation by the volcanic aerosol cloud. However, in the case of geoengineering here, the aerosol cloud is well-distributed in latitude (Figure 3), so there is not a large temperature gradient to produce a stronger polar vortex.

Figure 7 shows patterns of precipitation change for the Arctic 3 Mt/yr case. While most of the world shows little annual average change, there is still a significant reduction of precipitation in India (top left). In addition, there is a large reduction over India and northern China in the Northern Hemisphere summer, associated with the reduction of the summer monsoon, as discussed above, which is significant over India. As compared to the A1B case, there is also a significant reduction over the Sahel and over northern China and Japan (middle, right panel). The precipitation patterns for the Tropical 5 Mt/yr case are similar (Figure 8). The annual average patterns are similar to those of *Rasch et al.* [2008], but they did not examine the seasonal patterns.

Because of the observed rapid decrease in summer Arctic sea ice [*Kerr*, 2007], even larger than climate model predictions [*Vinnikov et al.*, 1999; *IPCC*, 2007; *Stroeve et al.*, 2007], one of the goals of proposed geoengineering is to prevent the disappearance of Arctic sea ice in the summer and the resultant large consequences for the entire ecosystem, including endangered or precarious indigenous species, such as polar bears and walruses. Figure 9 shows that both the Arctic 3 Mt/yr and Tropical 5 Mt/yr cases produce much more sea ice in September, the time of minimum sea ice extent. This is shown in the time series of September Arctic sea ice in Figure 10, which also shows rapid ice melting as soon as geoengineering stops.

5. Discussion and Conclusions

It is clear from our results that if enough aerosols could be put into the stratosphere, they would cool the planet and even reverse global warming (Figure 1). This brings up the question of what the optimal global climate should be, if we could control it. And who would decide?

Should it be the current climate? The pre-industrial climate? Figure 1 shows that if enough SO_2 could be continuously injected into the stratosphere, the global thermostat could be adjusted at any setting, but that if stopped at some time, say by lack of technical capability, political will, or discovery of unforeseen negative consequences, there would be even more rapid global warming than has occurred in the past century or than is projected with business as usual, as previously shown by *Wigley* [2006] and *Matthews and Caldeira* [2007]. Adaptation to such a rapid climate change would be difficult.

Tropical injection schemes could cool the global average climate. There would be more cooling over continental areas, as expected. But the consequences for the African and Asian summer monsoons could be serious, threatening the food and water supplies to billions of people.

The safety and efficacy of the recent suggestion of injection of sulfate aerosols into the Arctic stratosphere to prevent sea ice and Greenland from melting while avoiding adverse effects on the biosphere at lower latitudes [*Lane et al.*, 2007] are not supported by our results. While Arctic temperature could be controlled, and sea ice melting could be reversed, there would still be large consequences for the summer monsoons, since the aerosols would not be confined to the polar region.

Mitigation (reducing emissions of greenhouse gases) will reduce global warming, but is only now being seriously addressed by the planet. Whether we should use geoengineering as a temporary measure to avoid the most serious consequences of global warming requires a detailed evaluation of the benefits, costs, and dangers of different options. *MacCracken* [2006], *Bengtsson* [2006], *Cicerone* [2006], *Kiehl* [2006], and *Lawrence* [2006] all express concern about geoengineering. *Robock* [2008b] lists 20 reasons that argue against the implementation of this kind of geoengineering. The work here helps to document some benefits of geoengineering (global cooling and preservation of Arctic sea ice), but also the possible side effects on regional climate, item 1 on that list.

Acknowledgments. This work is supported by NSF grant ATM-0730452. We thank Phil Rasch, Ben Kravitz, Alvia Gaskill, Tom Wigley, Mark Lawrence, and an anonymous reviewer for valuable comments. Model development and computer time at GISS are supported by NASA climate modeling grants.

References

Angel, R. (2006), Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1), *Proc. Nat. Acad. Sci.*, *103*, 17,184-17,189.

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

Bluth G. J. S., S. D. Doiron, S. C. Schnetzler, A. J. Krueger, and L. S. Walter (1992), Global tracking of the SO_2 clouds from the June, 1991 Mount Pinatubo eruptions, *Geophys. Res. Lett.*, *19*, 151-154.

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

Boyd, P. W. (2000), A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization, *Nature*, *407*, 695-702.

Budyko, M. I. (1977), *Climatic Changes* (American Geophysical Union, Washington, DC), 261 pp.

Cicerone, R. J., S. Elliott, and R. P. Turco (1992), Global environmental engineering, *Nature*, *356*, 472.

Cicerone, R. (2006), Geoengineering: Encouraging research and overseeing implementation. *Climatic Change*, *77*, 221-226.

Crutzen, P. (2006), Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Climatic Change*, *77*, 211-219.

Dickinson, R. E. (1996) Climate engineering: A review of aerosol approaches to changing the global energy balance. *Climatic Change*, *33*, 279-290.

Environmental Pollution Panel (1965), *Restoring the Quality of Our Environment*, (The White House, Washington, D.C.), 292 pp.

Flannery, B. P., H. Kheshgi, G. Marland, and M. C. MacCracken (1997), Geoengineering Climate, Chap. 8 in *Engineering Response to Global Climate Change*, R. G. Watts, ed., (Lewis Publishers, New York), 379-427.

Fleming, J. R. (2004), Fixing the weather and climate: Military and civilian schemes for cloud seeding and climate engineering, in *The Technological Fix: How people use technology to create and solve problems*, Lisa Rosner, ed. (Routledge, New York), 175-200.

Fleming, J. R. (2006), The pathological history of weather and climate modification: Three cycles of promise and hype, *Historical Studies in the Physical Sciences*, **37**, 3-25.

Fleming, J. R. (2007), The climate engineers, *Wilson Quarterly*, Spring 2007, 46-60.

Gao, C., L. Oman, A. Robock, and G. L. Stenchikov (2007) Atmospheric volcanic loading derived from bipolar ice cores accounting for the spatial distribution of volcanic deposition. *J. Geophys. Res.*, *112*, D09109, doi:10.1029/ 2006JD007461.

Govindasamy, B., and K. Caldeira (2000), Geoengineering Earth's radiation balance to mitigate CO_2-induced climate change, *Geophys. Res. Lett.*, *27*, 2141-2144.

Govindasamy, B., S. Thompson, P. B. Duffy, K. Caldeira, and C. Delire (2002), Impact of geoengineering schemes on the terrestrial biosphere, *Geophys. Res. Lett.*, *29*, 2061, doi:10.1029/2002GL015911.

Govindasamy, B., K. Caldeira, and P. B. Duffy (2003), Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO_2, *Glob. Plan. Change*, *37*, 157-168.

Graf, H.-F., I. Kirchner, A. Robock, and I. Schult (1993), Pinatubo eruption winter climate effects: Model versus observations, *Climate Dynamics*, *9*, 81-93.

Hansen, J., R. Ruedy, M. Sato, and R. Reynolds (1996), Global surface air temperature in 1995: Return to pre-Pinatubo level, *Geophys. Res. Lett.*, *23*, 1665-1668, doi:10.1029/96GL01040.

Hansen, J., et al. (2005), Efficacy of climate forcings, *J. Geophys. Res.*, *110*, D18104, doi:10.1029/2005JD005776.

IPCC (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, Eds., (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA), 996 pp.

Keith, D. W. (2000), Geoengineering the climate: History and prospect, *Ann. Rev. Energy. Environ.*, *25*, 245-284.

Keith, D. (2001), Geoengineering, *Nature*, *409*, 420.

Kerr, R. A. (2007), Is battered Arctic sea ice down for the count? *Science*, *318*, 33-34.

Khan, E., et al. (2001), *Response Options to Limit Rapid or Severe Climate Change*, (Department of Energy, Washington, D.C.), 37 pp.

Kiehl, J. T. (2006), Geoengineering climate change: Treating the symptom over the cause? *Climatic Change*, *77*, 227-228.

Koch, D., G. A. Schmidt, and C. V. Field (2006), Sulfur, sea salt, and radionuclide aerosols in GISS ModelE, *J. Geophys. Res.*, *111*, D06206, doi:10.1029/2004JD005550.

Kodera, K., M. Chiba, H. Koide, A. Kitoh, and Y. Nikaidou (1996), Interannual variability of the winter stratosphere and troposphere in the northern hemisphere, *J. Meteorol. Soc. Jpn.*, *74*, 365-382.

Lane, L., K. Caldeira, R. Chatfield, and S. Langhoff, Editors (2007), *Workshop Report on Managing Solar Radiation*, NASA/CP–2007-214558, 31 pp.

Lawrence, M. G. (2006), The geoengineering dilemma: To speak or not to speak, *Climatic Change*, *77*, 246-248.

Leemans, R., S. Agrawal, J. A. Edmunds, M. C. MacCracken, R. Moss, and P. S. Ramakrishnan (1996), Mitigation: Cross-sectoral and other issues, Chapter 25 of *Climate Change 1995, Impacts Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Contribution of Working Group II to the Second IPCC Assessment*, R. T. Watson, M. C. Zinyowera and R. H. Moss, Eds., (Cambridge Univ. Press, UK), 799-819.

MacCracken, M. C. (2006), Geoengineering: Worthy of cautious evaluation? *Climatic Change*, *77*, 235-243.

Matthews, H. D., and K. Caldeira (2007), Transient climate–carbon simulations of planetary geoengineering, *Proc. Nat. Acad. Sci.*, *104*, 9949-9954, doi:10.1073/pnas.0700419104.

Mills, M. J., O. B. Toon, R. P. Turco, D. E. Kinnison, and R. R. Garcia (2008), Massive global ozone loss predicted following regional nuclear conflict, *Proc. Nat. Acad. Sci.*, in press.

Oman, L., A. Robock, G. Stenchikov, G. A. Schmidt, and R. Ruedy (2005), Climatic response to high latitude volcanic eruptions, *J. Geophys. Res, 110* (D13), D13103, doi:10.1029/ 2004JD005487.

Oman, L., A. Robock, G. L. Stenchikov, and T. Thordarson (2006a), High-latitude eruptions cast shadow over the African monsoon and the flow of the Nile, *Geophys. Res. Lett.*, *33*, L18711, doi:10.1029/2006GL027665.

Oman, L., A. Robock, G. Stenchikov, T. Thordarson, D. Koch, D. Shindell and C. Gao (2006b), Modeling the distribution of the volcanic aerosol cloud from the 1783-1784 Laki eruption, *J. Geophys. Res*., *111*, D12209, doi:10.1029/2005JD006899.

Panel on Policy Implications of Greenhouse Warming, Committee on Science, Engineering, and Public Policy, National Academy of Sciences (1992), *Policy Implications of Greenhouse*

Warming: Mitigation, Adaptation, and the Science Base (National Academy Press, Washington, D.C.), 433-464.

Rasch, P. J., P. J. Crutzen, and D. B. Coleman (2008), Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size, *Geophys. Res. Lett.*, *35*, L02809, doi:10.1029/2007GL032179.

Robock, A., and Y. Liu (1994), The volcanic signal in Goddard Institute for Space Studies three-dimensional model simulations, *J. Climate*, *7*, 44-55.

Robock, A. (2000), Volcanic eruptions and climate, *Rev. Geophys.*, *38*, 191-219.

Robock, A. (2008a), Whither geoengineering? *Science*, in press.

Robock, A. (2008b), 20 reasons why geoengineering may be a bad idea, *Bull. Atomic Scientists*, *64*, No. 2, 14-18, 59, doi:10.2968/064002006.

Robock, A., L. Oman, G. L. Stenchikov, O. B. Toon, C. Bardeen, and R. P. Turco (2007a), Climatic consequences of regional nuclear conflicts. *Atm. Chem. Phys.*, *7*, 2003-2012.

Robock, A., L. Oman, and G. L. Stenchikov (2007b), Nuclear winter revisited with a modern climate model and current nuclear arsenals: Still catastrophic consequences. *J. Geophys. Res.*, *112*, D13107, doi:10.1029/2006JD008235.

Rusin, N., and L. Flit (1960), *Man Versus Climate*, (Peace Publishers, Moscow), 175 pp.

Russell, G. L., J. R. Miller, and D. Rind (1995), A coupled atmosphere-ocean model for transient climate change, *Atmos.-Ocean*, *33*, 683-730.

Schmidt, G. A., et al. (2006), Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data, *J. Clim.*, *19*, 153-192.

Schneider, S. H. (1996), Geoengineering: Could – or should – we do it? *Climatic Change*, *33*, 291-302.

Schneider, S. H. (2001), Earth systems: Engineering and management, *Nature*, *409*, 417-419, 421.

Solomon, S. (1999), Stratospheric ozone depletion: A review of concepts and history, *Rev. Geophys.*, *37*, 275-316.

Stenchikov, G. L., I. Kirchner, A. Robock, H.-F. Graf, J. C. Antuña, R. G. Grainger, A. Lambert, and L. Thomason, 1998: Radiative forcing from the 1991 Mount Pinatubo volcanic eruption, *J. Geophys. Res.*, *103*, 13,837-13,857.

Stenchikov, G., A. Robock, V. Ramaswamy, M. D. Schwarzkopf, K. Hamilton, and S. Ramachandran (2002), Arctic Oscillation response to the 1991 Mount Pinatubo eruption: Effects of volcanic aerosols and ozone depletion, *J. Geophys. Res.*, *107*, 4803, doi:10.1029/2002JD002090.

Stenchikov, G., K. Hamilton, A. Robock, V. Ramaswamy, and M. D. Schwarzkopf (2004), Arctic Oscillation response to the 1991 Pinatubo eruption in the SKYHI GCM with a realistic Quasi-Biennial Oscillation, *J. Geophys. Res.*, *109*, D03112, doi:10.1029/2003JD003699.

Stenchikov, G., K. Hamilton, R. J. Stouffer, A. Robock, V. Ramaswamy, B. Santer, and H.-F. Graf (2006), Arctic Oscillation response to volcanic eruptions in the IPCC AR4 climate models, *J. Geophys. Res.*, *111*, D07107, doi:10.1029/2005JD006286.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, *34*, L09501, doi:10.1029/2007GL029703.

Teller, E., L. Wood, and R. Hyde (1997), *Global Warming and Ice Ages: I. Prospects for Physics-Based Modulation of Global Change*, Lawrence Livermore National Laboratory Publication UCRL-JC-128715, 18 pp.

Teller, E., et al. (1999), *Long-Range Weather Prediction and Prevention of Climate Catastrophes: A Status Report*. Lawrence Livermore National Laboratory Publication UCRL-JC-135414, 44 pp.

Teller, E., R. Hyde, and L. Wood (2002), *Active Climate Stabilization: Practical Physics-Based Approaches to Prevention of Climate Change*, Lawrence Livermore National Laboratory Publication UCRL-JC-148012, 8 pp.

Thompson, D. W. J., and J. M. Wallace (1998), The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297-1300.

Tilmes, S., R. Müller, and R. Salawitch (2008), The sensitivity of polar ozone depletion to proposed geoengineering schemes, *Science,* doi:10.1126/science.1153966.

Trenberth, K. E., and A. Dai (2007), Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering, *Geophys. Res. Lett.*, *34*, L15702, doi:10.1029/2007GL030524.

Turco, R. P. (1995), Global environmental engineering: Prospects and pitfalls, Chapter 7, *Human Population and the Environmental Crisis*, B. Zuckerman and D. Jefferson (eds.), (Jones and Bartlett Publ., Sudbury, Mass.), pp. 93-113.

Vinnikov, K. Y., A. Robock, R. J. Stouffer, J. E. Walsh, C. L. Parkinson, D. J. Cavalieri, J. F. B. Mitchell, D. Garrett, and V. F. Zakharov (1999), Global warming and Northern Hemisphere sea ice extent, *Science*, *286*, 1934-1937.

Wigley, T. M. L. (2006), A combined mitigation/geoengineering approach to climate stabilization, *Science, 314*, 452-454.

Yang, F., A. Kumar, M. E. Schlesinger, and W. Wang (2003), Intensity of hydrological cycles in warmer climates, *J. Climate*, *16*, 2419–2423.

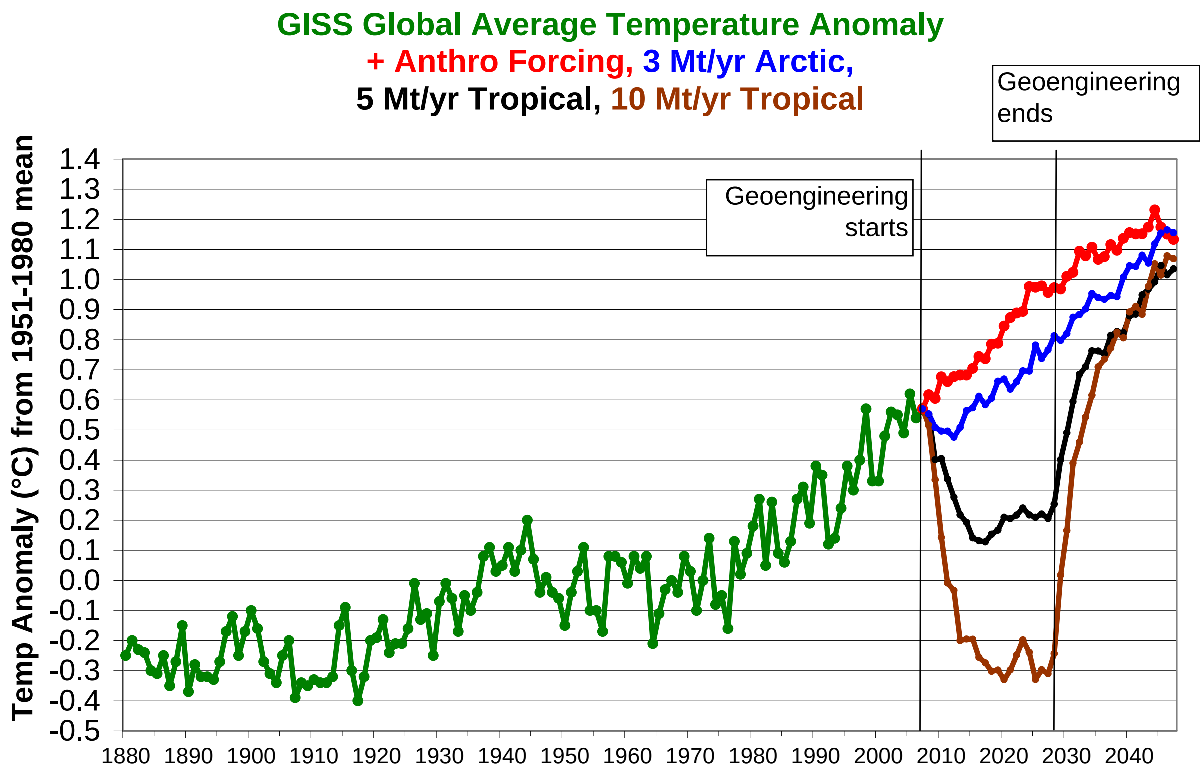

Figure 1. Global average surface air temperature change from the A1B anthropogenic forcing run (red), Arctic 3 Mt/yr SO_2 (blue), Tropical SO_2 5 Mt/yr (black), and Tropical 10 Mt/yr SO_2 (brown) cases in the context of the climate change of the past 125 years. Observations (green) are from the National Aeronautics and Space Administration Goddard Institute for Space Studies analysis [*Hansen et al.*, 1996, updated at http://data.giss.nasa.gov/gistemp/2007/].

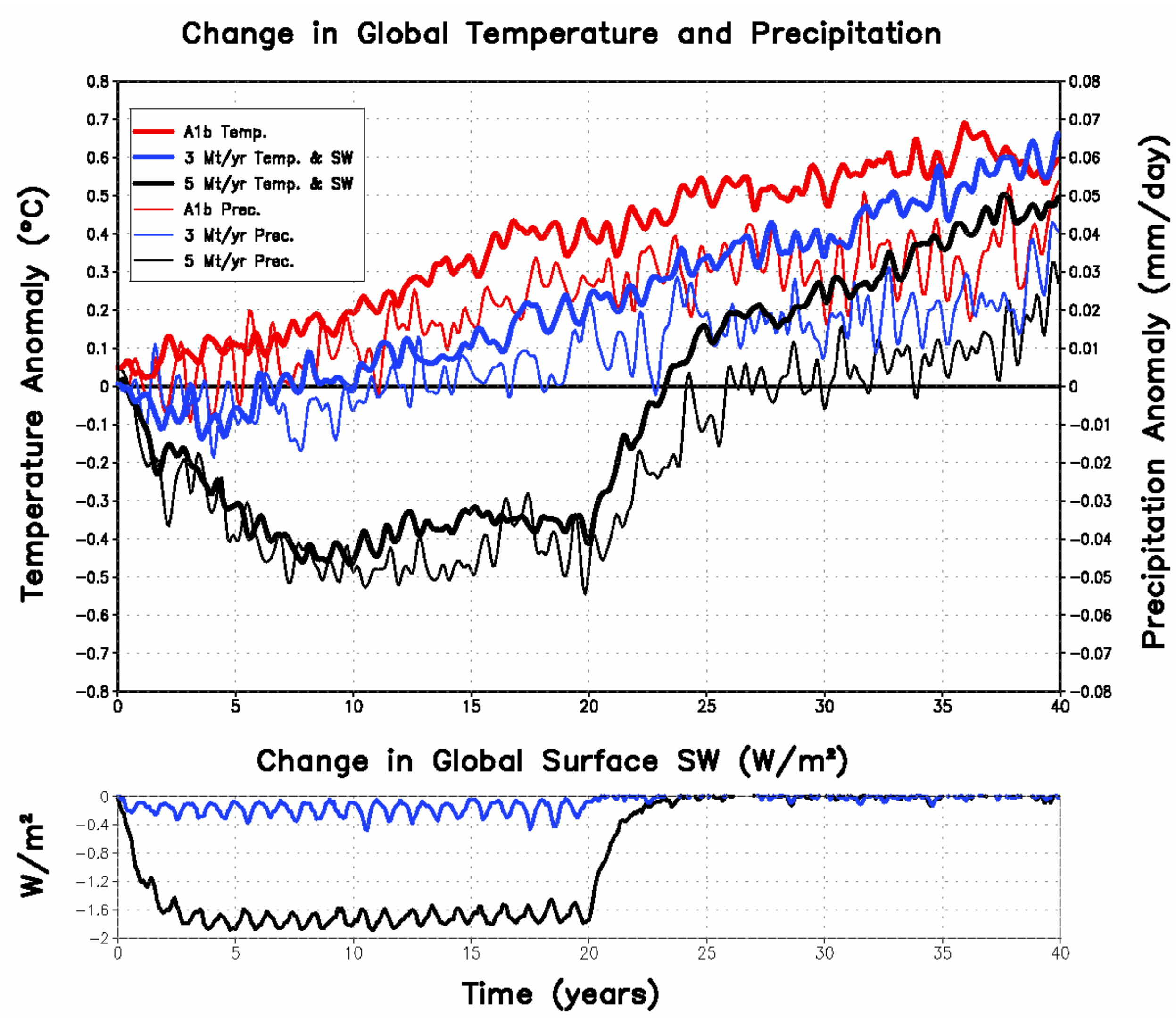

Figure 2. Global, monthly average changes (compared to the control run) in temperature (thick lines) and precipitation (thin lines) for A1B (red), Arctic 3 Mt/yr (blue) and Tropical 5 Mt/yr (black) runs, and change in downward solar radiation at the surface (as compared to the A1B runs) for the Arctic 3 Mt/yr (blue) and Tropical 5 Mt/yr (black) runs.

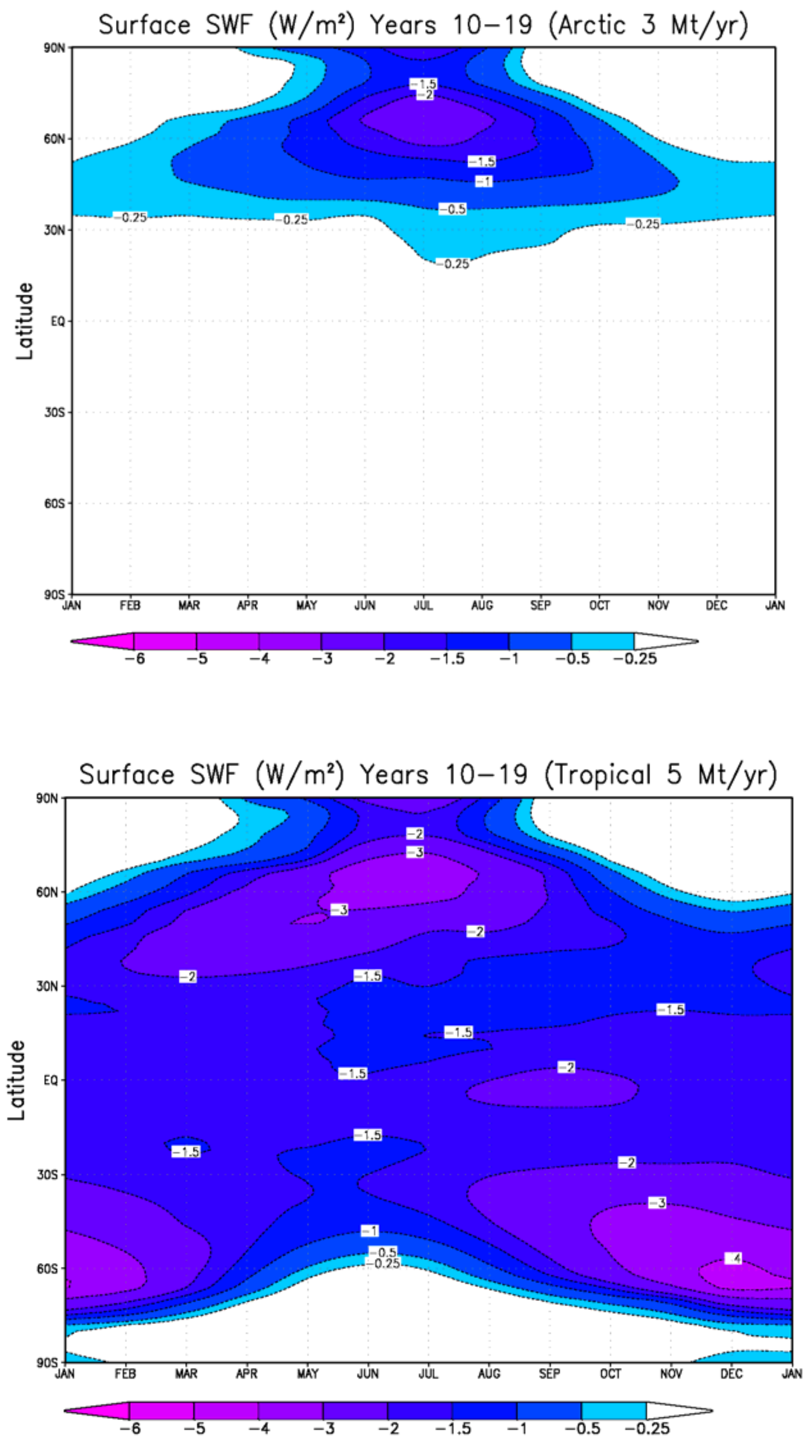

Figure 3. Change in downward surface shortwave flux from the Arctic 3 Mt/yr and Tropical 5 Mt/yr runs, as a function of latitude and month, averaged for the second 10 years of the 20-yr period during which the geoengineering was applied.

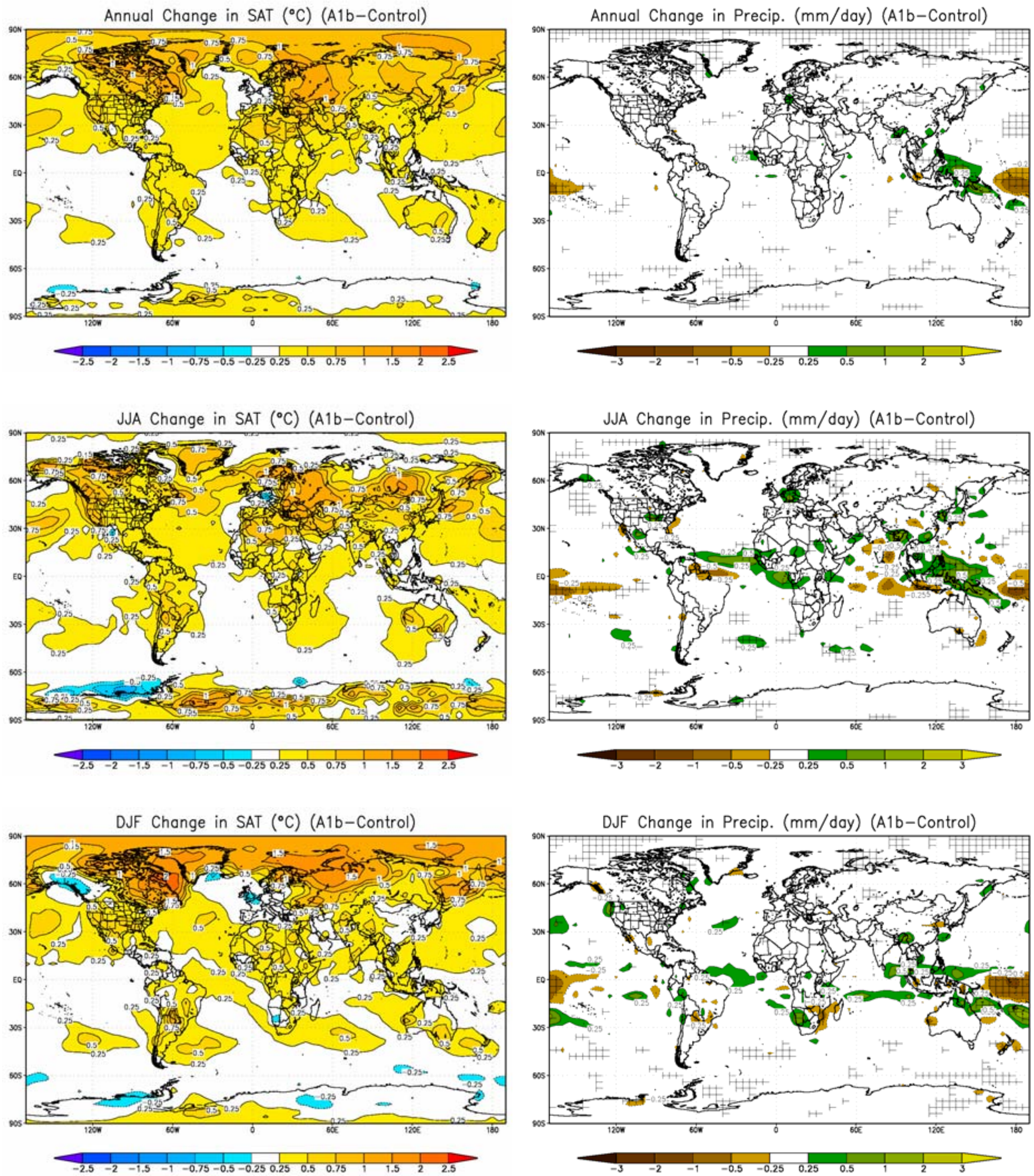

Figure 4. Surface air temperature change (left column) and precipitation change (right column) for A1B run compared to the control run, averaged for the second 10 years of the 20-yr geoengineering period, for annual average (top), Northern Hemisphere summer (middle), and Northern Hemisphere winter (bottom). Hatch marks on precipitation plots indicate changes significant at the 5% level.

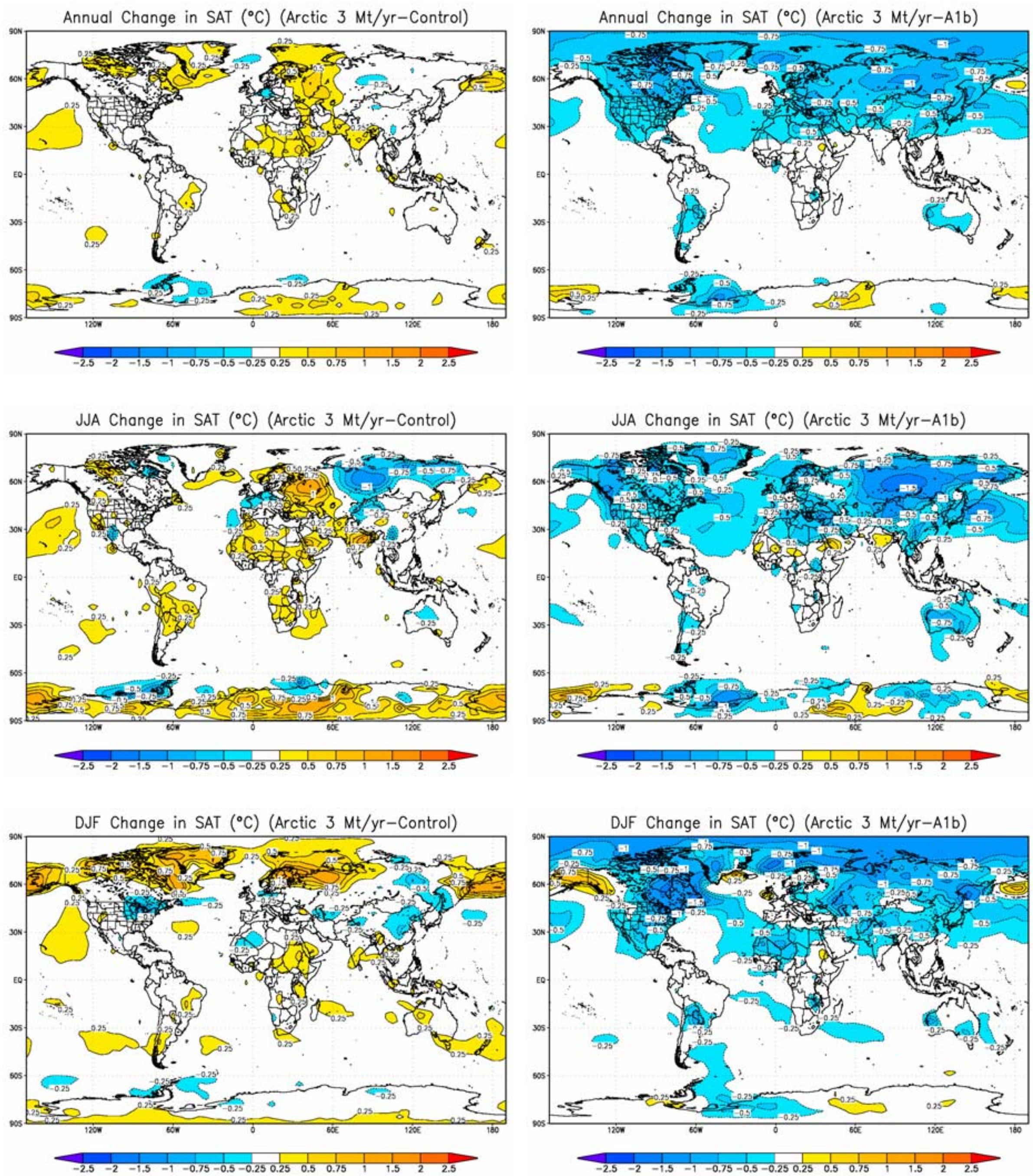

Figure 5. For the Arctic 3 Mt/yr runs, annual average (top row), Northern Hemisphere summer (middle row), and Northern Hemisphere winter (bottom row) surface air temperature differences from the control climate (left column) and from the A1B runs (right column), averaged for the second 10 years of the 20-yr geoengineering period.

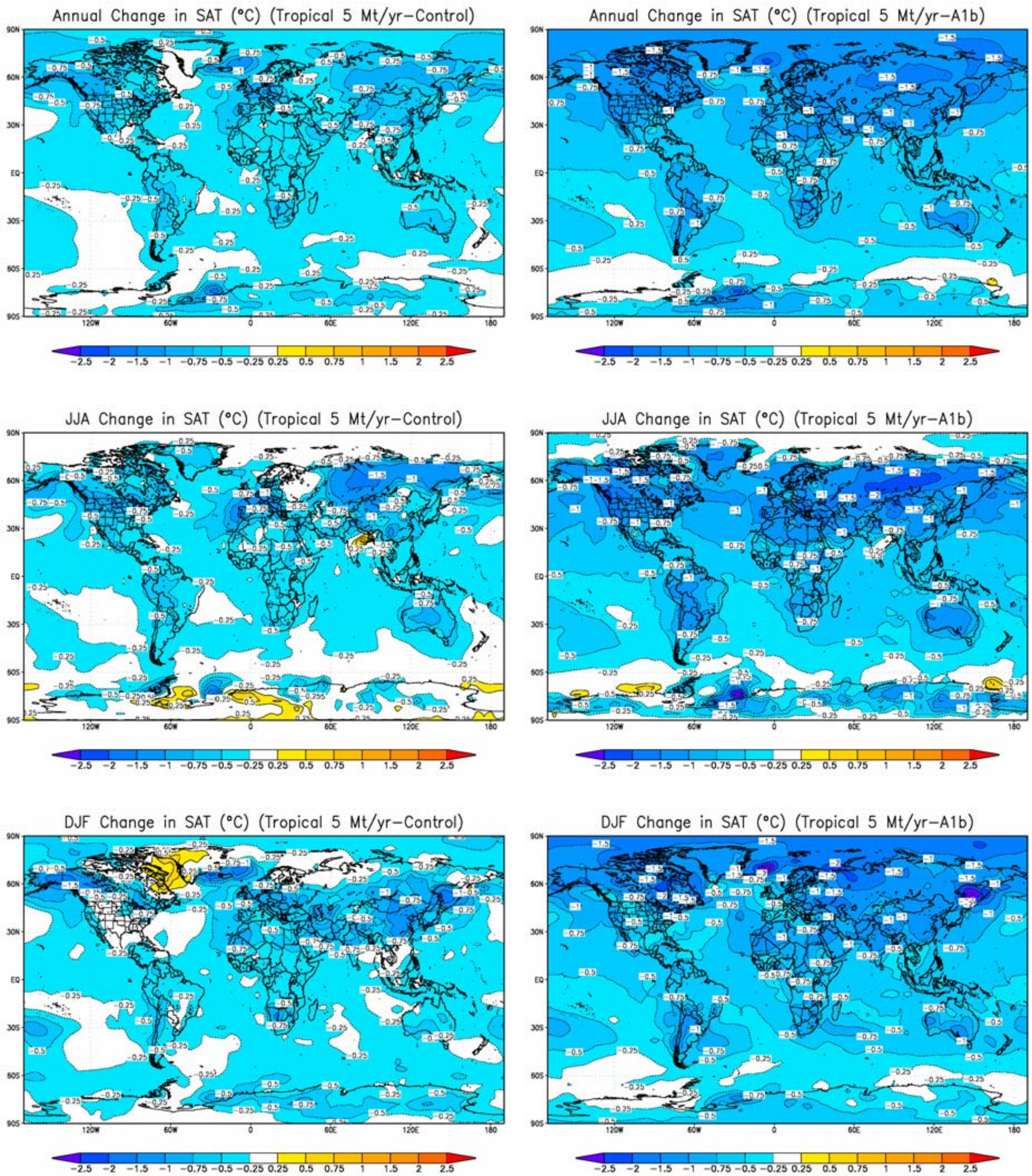

Figure 6. For the Tropical 5 Mt/yr runs, annual average (top row), Northern Hemisphere summer (middle row), and Northern Hemisphere winter (bottom row) surface air temperature differences from the control climate (left column) and from the A1B runs (right column), averaged for the second 10 years of the 20-yr geoengineering period.

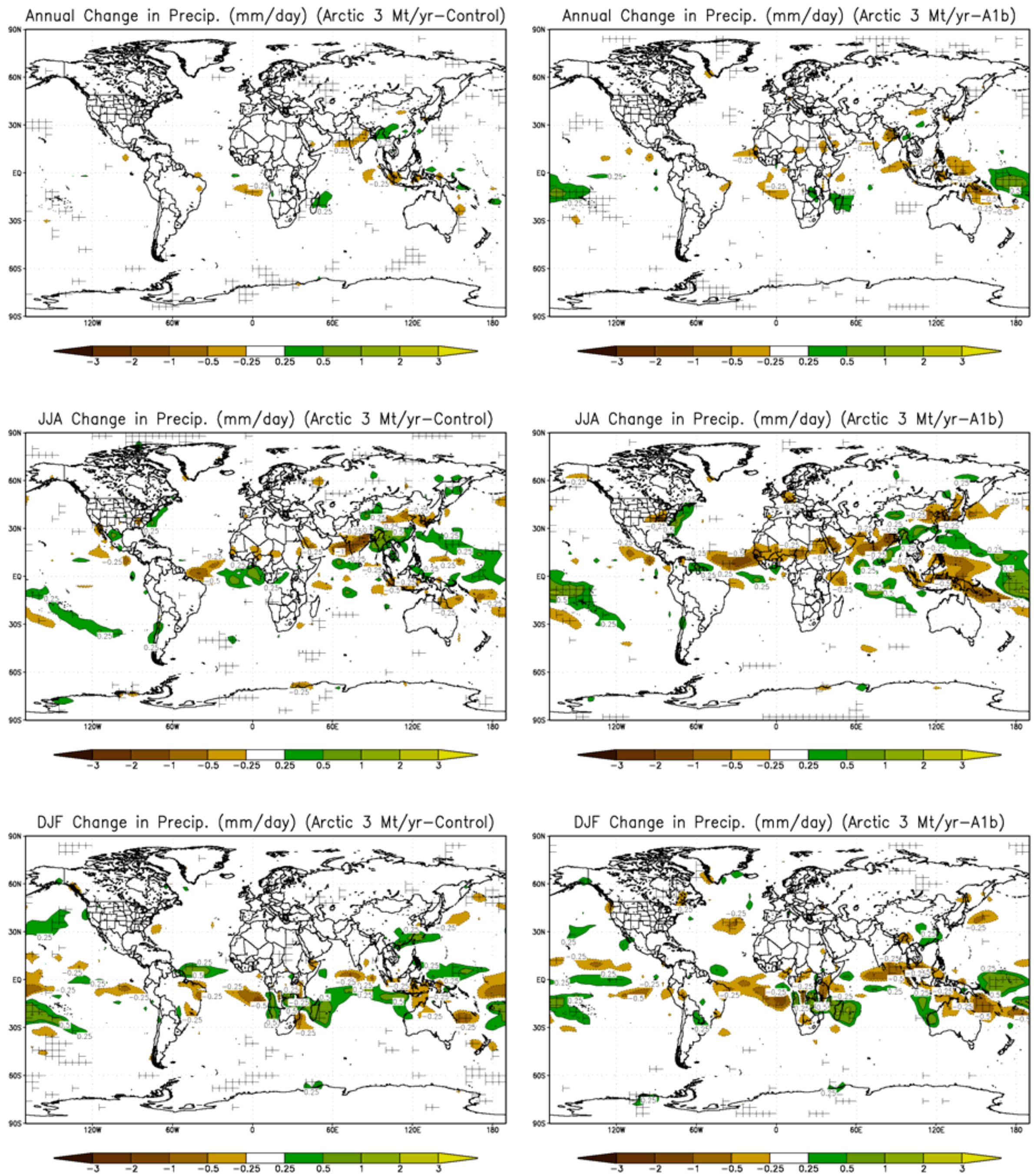

Figure 7. For the Arctic 3 Mt/yr runs, annual average (top row), Northern Hemisphere summer (middle row), and Northern Hemisphere winter (bottom row) precipitation differences from the control climate (left column) and from the A1B runs (right column), averaged for the second 10 years of the 20-yr geoengineering period. Hatch marks indicate changes significant at the 5% level.

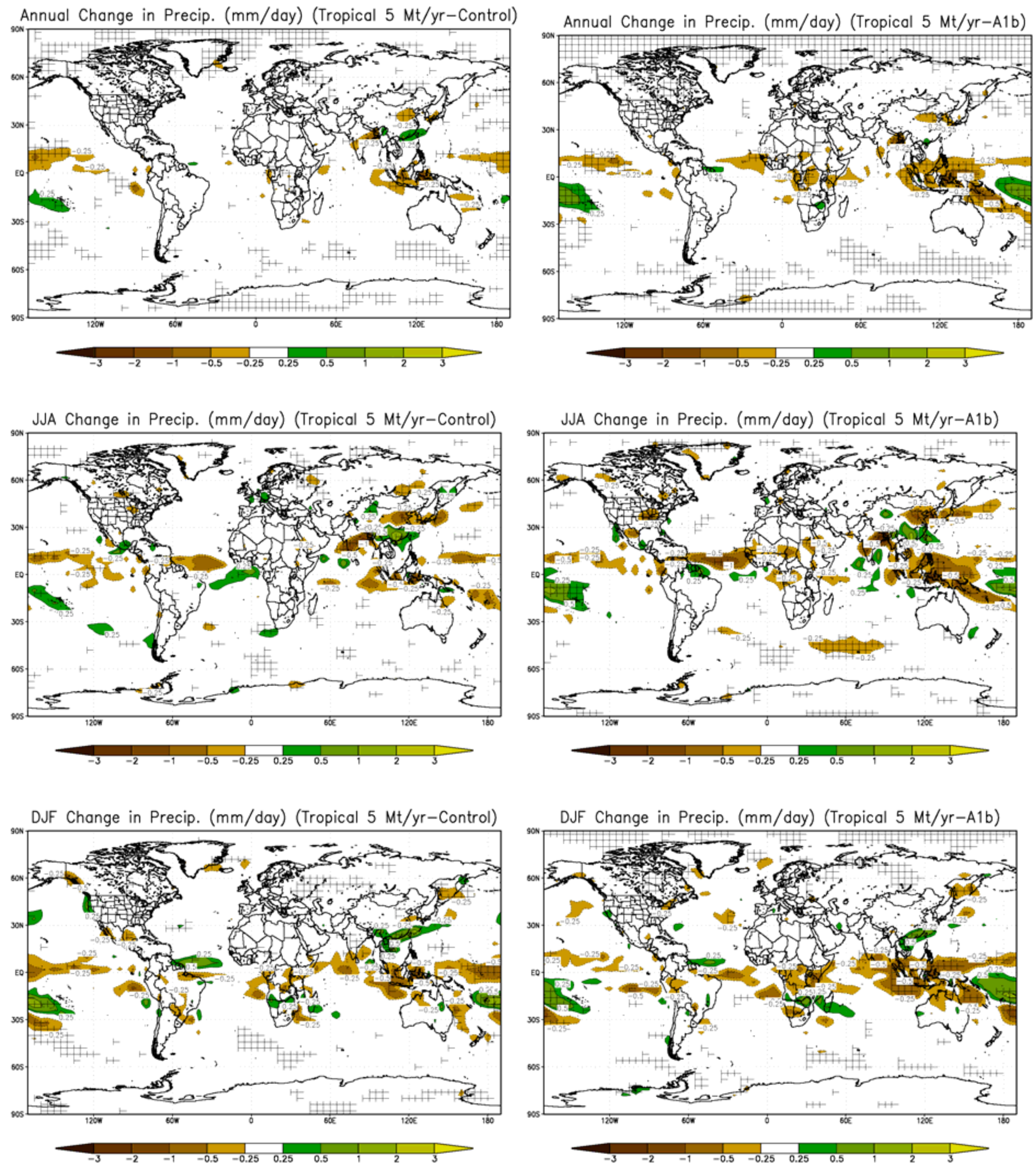

Figure 8. For the Tropical 5 Mt/yr runs, annual average (top row), Northern Hemisphere summer (middle row), and Northern Hemisphere winter (bottom row) precipitation differences from the control climate (left column) and from the A1B runs (right column), averaged for the second 10 years of the 20-yr geoengineering period. Hatch marks indicate changes significant at the 5% level.

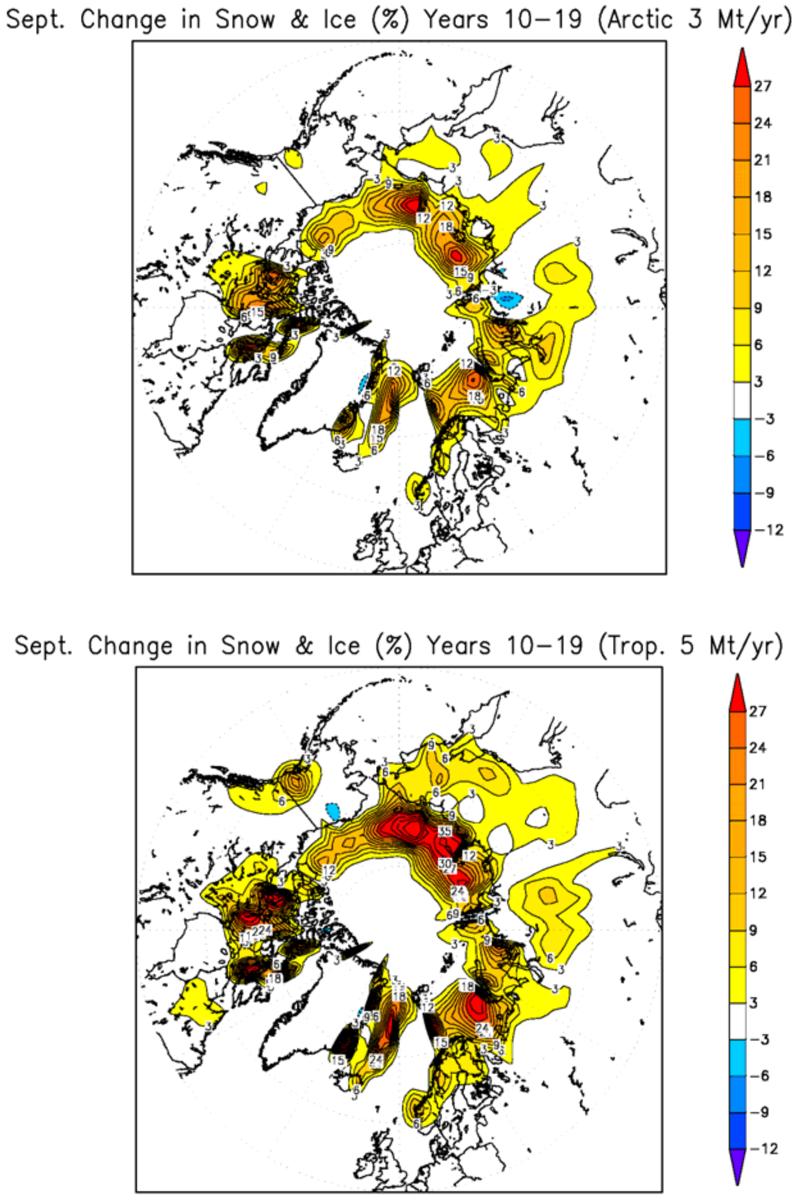

Figure 9. Change of September Arctic sea ice coverage, as compared to the A1B run, for the Arctic 3 Mt/yr and Tropical 5 Mt/yr runs, averaged for the second 10 years of the 20-yr geoengineering period. Units are % of total coverage, not of the A1B values.

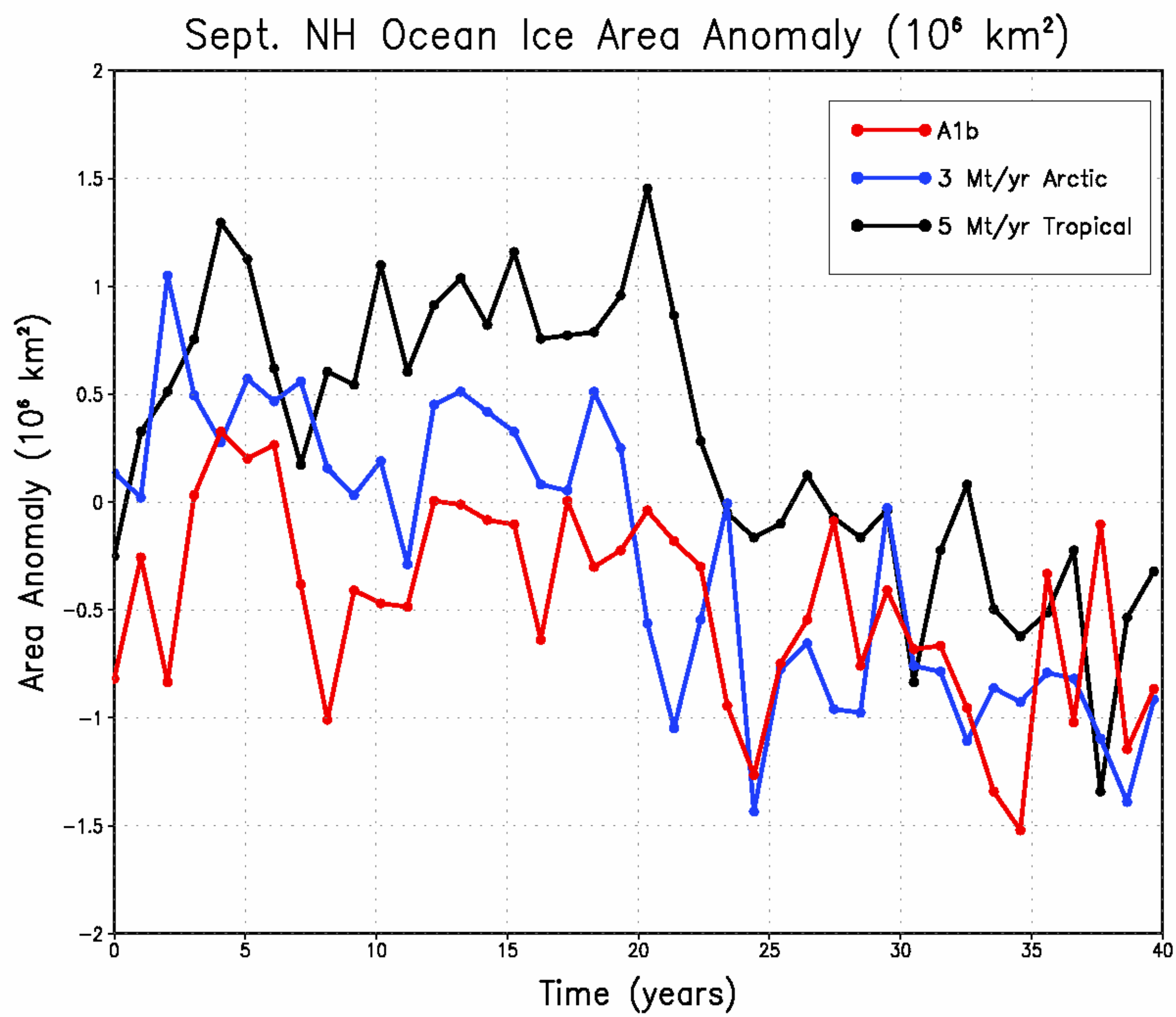

Figure 10. Time series of September Arctic sea ice area for the different experiments.