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Climate response to imposed solar radiation reductions in high latitudes

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Abstract

Increasing concentrations of greenhouse gases are the primary contributor to the 0.8 °C increase in the global average temperature since the late 19th century, shortening cold seasons and lengthening warm seasons. The warming is amplified in polar regions, causing retreat of sea ice, snow cover, permafrost, mountain glaciers, and ice sheets, while also modifying mid-latitude weather, amplifying global sea level rise, and initiating high-latitude carbon feedbacks. Model simulations in which we reduced solar insolation over high latitudes not only cooled those regions, but also drew energy from lower latitudes, exerting a cooling influence over much of the hemisphere in which the reduction was imposed. Our simulations, which used the National Center for Atmospheric Research's CAM3.1 atmospheric model coupled to a slab ocean, indicated that, on a normalized basis, high-latitude reductions in absorbed solar radiation have a significantly larger cooling influence than equivalent solar reductions spread evenly over the Earth. This amplified influence occurred because high-latitude surface cooling preferentially increased sea ice fraction and, therefore, surface albedo, leading to a larger deficit in the radiation budget at the top of the atmosphere than from an equivalent global reduction in solar radiation. Reductions in incoming solar radiation in one polar region (either north or south) resulted in increased poleward energy transport during that hemisphere's cold season and shifted the Inter-Tropical Convergence Zone (ITCZ) away from that pole, whereas equivalent reductions in both polar regions tended to leave the ITCZ approximately in place. Together, these results suggest that, until emissions reductions are sufficient to limit the warming influence of greenhouse gas concentrations, polar reductions in solar radiation, if they can be efficiently and effectively implemented, might, because of fewer undesirable side effects than for global solar radiation reductions, be a preferred approach to limiting both high-latitude and global warming.

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1 Introduction

Increases in the atmospheric concentrations of carbon dioxide and other radiatively active substances have initiated changes in the global climate that are projected to become substantially larger in the future (IPCC, 2007a). Not only are surface temperatures increasing, but significant shifts are also being observed in mean precipitation, in extreme precipitation and drought, in snow and sea ice extent and duration, in sea level, and in ocean acidification. Taken together, these changes are starting to adversely impact water resources, agriculture, terrestrial and aquatic ecosystems, coastal infrastructure, and human health (IPCC, 2007b). In general, changes in climate and the impacts on ice mass, ecosystems and communities are being amplified in high latitudes (ACIA, 2004; AMAP, 2011), with the larger responses then contributing to the additional changes and impacts at lower latitudes.

International proposals to limit emissions to halt climate change go back to the 1970s (e.g., SMIC, 1971) and international recognition that mitigation would not be adequate to avoid adaptation dates back to the 1980s (e.g., WMO, 1985). The UN Framework Convention on Climate Change adopted in 1992 and the follow-on Kyoto Protocol negotiated in 1997 were intended to cut growth in global emissions, but have had only limited success (IPCC 2007c). Despite the intensified negotiations, global greenhouse gas emissions have continued to increase (Friedlingstein et al., 2010), and atmospheric concentrations are projected to continue to increase for at least the next several decades, if not longer (IPCC, 2007c). As a result, global average temperature is on a path to exceed 2–3 °C by the latter decades of the 21st century, with warming continuing into the 22nd century (Meinshausen et al., 2009). Unless aggressive reductions in emissions begin soon, the probability of disruptive and even "dangerous" impacts to the environment and society is likely to increase significantly (Lenton et al., 2008).

The potential for counter-balancing the warming influences of greenhouse gases was first suggested in the 1960s (PSAC, 1965; Budyko, 1969, 1974) and again received attention in the 1990s (NAS, 1992; Leemans et al., 1995; Flannery et al., 1997; Keith,

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2000; Schneider, 2001). Virtually no research was undertaken as a result of these studies, however, and, until recently, the sheer hubris of even considering taking control of the climate has tended to suppress serious consideration of proposed approaches. Discouraged by the lack of progress in international negotiations to limit greenhouse gas emissions, Wigley (2006) and Crutzen (2006) resurrected the call for research into potential approaches for limiting climate change. Since their papers, approaches to *geoengineering* (although perhaps more appropriately labeled *climate engineering*) have received increased, although still quite limited, attention and investigation. In addition, a number of high-level review groups have called for increased research to determine the potential strengths and weaknesses of the various proposed approaches (e.g., Royal Society, 2009; GAO, 2010; Long et al., 2011), while other groups have urged consideration of the ethical, governance, and other implications of conducting such research (e.g., Robock et al., 2009; Asilomar, 2010; Rayner et al., 2010).

The full range of possible climate engineering approaches includes efforts to increase the removal of CO_2 and other greenhouse gases from the atmosphere (an approach generally referred to as Carbon Dioxide Reduction, or CDR) and efforts to reduce the uptake and retention of energy by the Earth system (an effort generally referred to as Solar Radiation Management, or SRM); see MacCracken (2009a) and Royal Society (2010) for recent overviews. Mitchell and Finnegan (2009) have suggested that the global average surface temperature could also be lowered by reducing the global coverage of cirrus clouds, thereby increasing emission of long-wave radiation rather than reducing incoming solar radiation.

In this paper we investigate a polar-focused approach to SRM, and do not further consider other alternatives to limiting the pace of climate change. The next section briefly summarizes possible approaches to global SRM, focusing primarily on the major unintended consequences that have been associated with augmenting the global stratospheric sulfate loading because moderating these consequences is the primary rationale for our exploration of the potential for polar-focused approaches. The third section describes the results of our model simulations, comparing the potential for

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counter-balancing global climate change by global and polar reductions in solar radiation. The fourth section presents an analysis of the relative effectiveness in offsetting global climate change of the global and polar approaches. The fifth section discusses the relative merits of the two approaches and the sixth suggests next steps needed in the investigation and consideration of a polar-focused approach.

2 Rationale for a polar-focused approach

Initial SRM studies have used global climate models to investigate the potential for counter-balancing changes in global average temperature resulting from a doubled or rising atmospheric CO_2 concentration (e.g., Govindasamy and Caldeira, 2000; Caldeira and Wood, 2008). Consistent with earlier studies (e.g., Manabe and Wetherald, 1980; Hansen et al., 1997), these studies found that a latitudinally and seasonally uniform reduction in global-average solar insolation of ~1.8 to 2 % would approximately counteract the increase in global average temperature from a CO_2 doubling.

Proposed approaches for actually effecting this reduction include increasing the global loading of stratospheric aerosols (e.g., as studied by Rasch et al., 2008b; Robock et al., 2008; Jones et al., 2010), brightening marine stratus clouds by modifying the number or size of cloud condensation nuclei (CCN) (Latham et al., 2008; Bala et al., 2010), and brightening the ocean surface using microbubbles (Seitz, 2011). Augmenting the global tropospheric loading of sulfate aerosols, which currently exerts a cooling influence of order $-1\,\mathrm{Wm^{-2}}$ (Forster and Ramaswamy, 2007), could also be included as a potential approach, although the increased loading would need to be accomplished by other than increasing SO_2 emissions from coal-fired power plants to avoid emissions of CO_2 and other combustion products. Because volcanic eruptions demonstrate that the lifetime of stratospheric aerosols is typically 1 to 2 yr rather than 1 to 2 weeks for tropospheric aerosols, only 1–2 % as much sulfur (e.g., as SO_2) would need to be injected to sustain a stratospheric as compared to a radiatively equivalent

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tropospheric aerosol layer. In addition, the reduced health effects of atmospheric sulfur also likely favor the stratosphere option. Estimates are that the direct cost of injection of sulfur compounds into the stratosphere would be unlikely to be a major consideration in a decision whether or not to deploy such a system (e.g., NAS, 1992; McClellan et al., 2010), further favoring use of a stratospheric approach as the optimal approach to counter-balance global warming.

Cloud brightening by injection of sea salt aerosols is likely to have its largest effect in areas with relatively clean air and vast extents of low-level marine stratus clouds. In such areas, which, for example, extend far off the west coasts of North and South America, satellite observations suggest that ship exhaust, which increases the boundary layer CCN concentration, has the potential to significantly increase the albedo of marine stratus clouds for up to several days (Schreier et al., 2006). For injection of air bubbles into the ocean, which is an attempt to increase surface albedo as occurs in a ship's wake, the expected lifetime of various size bubbles is a critical uncertainty. Determining the comparable effectiveness of over-seeding the upper troposphere with ice nuclei in order to reduce cirrus cloud trapping of long-wave radiation has yet to tested, but the shorter lifetimes of tropospheric than stratospheric materials and the constant reintroduction of water vapor into the upper troposphere by convection suggest that this approach is likely to be more demanding than augmentation of the global stratospheric aerosol loading.

While augmenting the stratospheric aerosol layer appears to be the most plausible option for global SRM (GSRM), model simulations project a number of potentially significant unintended consequences (Robock et al., 2009). First, GSRM together with high GHG concentrations would reduce the amount of energy reaching the surface, but not the additional GHG-induced trapping of infrared radiation in the upper troposphere, thus tending to stabilize the troposphere and reduce the vertical energy gradient that drives the hydrological cycle. In addition, reduction in the land-sea temperature gradient might well weaken the summer monsoon circulation in Asia and North America

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relative to the high-CO_2 climate without GSRM, and even relative to the preindustrial climate (e.g., Bala et al., 2008; Robock et al., 2008).

A second major unintended consequence, at least for approaches that imitate volcanic eruptions by increasing the stratospheric aerosol loading, would be substantially increasing the diffuse fraction of the solar radiation transmitted downward to the surface (Olmo et al., 1999). In addition to potential poorly understood ecological impacts (Gu et al., 2003), this would reduce the energy that could be generated from solar technologies that, for example, use mirrors to concentrate the direct solar beam.

A third potential unintended consequence might well be impacting the stratospheric ozone layer, or at least slowing its recovery from past and ongoing emissions of chlorofluorcarbons and other halocarbons (Tilmes et al., 2008; Heckendorn et al., 2009; Tilmes et al., 2009). The depletion would result from catalytic reactions on the injected stratospheric aerosols, which the stratospheric circulation would be carrying from their likely injection points in low and middle latitudes toward the polar regions, where the aerosols would be preferentially removed by downward transport into the troposphere. Whether the latitudinal and seasonal timing of stratospheric injections or the types of reflective particles could be adjusted to minimize potential springtime depletion of ozone has yet to be determined.

To minimize at least some aspects of these adverse consequences, a possible iteration to imposing a globally uniform reduction in solar radiation would be to restrict the reductions to the polar regions during their peak sunlit periods, when the total daily solar insolation at high latitudes roughly matches that at low latitudes. Simulations by Caldeira and Wood (2008) indicated that large reductions in solar radiation over just the Arctic region had the potential to roughly offset not only the projected increase in Arctic temperature from a CO_2 doubling, but to also moderate the warming over Northern Hemisphere mid-latitudes. Further simulations by Irvine et al. (2009) indicated that Arctic solar reduction could offset polar warming even in the case of a quadrupled atmospheric CO_2 concentration.

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These results suggest that it might be possible to moderate global climate change, especially some of the substantial impacts in the Arctic that have the potential to impact the global climate (e.g., amplified warming, sea ice retreat, glacier and ice sheet melting, permafrost thawing), without inducing many of the unintended consequences of augmenting the global sulfate layer (MacCracken, 2009b). Conceptually, the notion is that reductions in absorbed solar energy in polar regions would cool those latitudes, which would increase the meridional temperature gradient and, as a consequence, draw more energy from lower latitudes, thus exerting a cooling influence on those regions. While most of the increased energy transport would occur during the winter months when the meridional temperature gradient is largest, the induced moderation of ocean warming would tend to limit the GHG-induced increase in mid- and low-latitude temperatures throughout the year.

For several reasons, fewer unintended environmental consequences would be expected for Arctic rather than global reductions in solar radiation. First, because evaporation occurs primarily in low- to mid-latitudes, restricting the reduction in solar radiation to high latitudes would be less likely to reduce the intensity of the global hydrologic cycle than would a global reduction in solar radiation. Indeed, the simulations of Caldeira and Wood (2008) indicated that, while Arctic temperatures were reduced with reductions in polar insolation, high-latitude precipitation tended to remain at the elevated level caused by the CO_2 doubling, with a greater fraction of the precipitation falling as snow. Were build-up of mountain glaciers and ice sheets to result from increased polar snowfall, slowing sea level rise would be an important global benefit in addition to moderating the increase in global average temperature.

In addition, if increasing the high-latitude sulfate loading in the lower stratosphere or troposphere were the approach to be used to reduce the region's absorption of solar radiation, then the inadvertent conversion of direct to diffuse radiation and associated unintended consequences would be limited to high-latitude regions where clouds and the high albedo of snow and ice already create a high fraction of diffuse radiation. In addition, in contrast to the reduction in the Asian summer monsoon resulting from a

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global solar reduction as found in the simulations reported by Robock et al. (2008), the intensity of summertime solar radiation striking mid-latitude land areas would not be diminished, suggesting that the monsoons would not be directly impacted.

While limiting the solar reductions to the Arctic may avoid direct consequences on lower latitudes, drawing additional energy into just one polar region would create a hemispheric energy imbalance that would be expected to lead to a latitudinal displacement of the rain-producing Inter-tropical Convergence Zone (ITCZ). To moderate this potential unintended consequence, we investigate whether imposing reductions in solar radiation in both the northern and southern polar regions together would lead to fewer impacts than imposing a global-average or Northern Hemisphere only solar reduction.

3 Model simulations

For this study, we used Version 3.1 of the National Center for Atmospheric Research Community Atmosphere Model, coupled to a slab ocean model (Collins et al., 2006). This version has a horizontal resolution of 2.8° in latitude by 2.58° in longitude and has 26 vertical levels. The land surface component calculates energy and water fluxes based on surface vegetation, soil moisture and the CO_2 concentration. Sea ice cover is calculated based on thermodynamic balances, but the effects of sea ice movement are not considered. This configuration of the model is the same as in Caldeira and Wood (2008), as were initial and other conditions.

As was the case for Caldeira and Wood (2008), the studies described here are intended to explore the potential response of the climate to reductions in solar energy input, whatever the technique to accomplish the reductions might be. As reported by Rasch et al. (2008a), Robock et al. (2008) and Pierce et al. (2010), the detailed physics and chemistry of actually trying to augment the background stratospheric aerosol loading, were that the specific approach to be used, could introduce additional complications that merit attention when moving beyond an idealized analysis. In spite of the

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idealization, studies of this type have the potential to provide important qualitative insights into questions such as the relative effects of possible alternative distributions of the imposed reductions in solar forcing.

To provide a baseline for considering the model's responses, we carried out two control simulations, one for the preindustrial atmospheric CO_2 concentration of 280 ppm ($1 \times CO_2$) and one for a world with a doubled CO_2 concentration ($2 \times CO_2$). To investigate the sensitivity to high-latitude solar reductions, we started from the $2 \times CO_2$ simulation. In addition to the global simulations, we separately imposed nine different high-latitude reductions in incoming top-of-the-atmosphere (TOA) solar radiation by amounts depending on the latitudinal ranges of the reduction. Three different high-latitude domains in the Northern (N) and Southern (S) Hemispheres were considered, with solar reductions imposed both separately in the two hemispheres and together (NS). As summarized in Table 1, the regional insolation reductions were: 25 % reduction over the Northern and Southern Hemisphere regions poleward of 71° (71p25), 10 % reduction poleward of 61° (61p10), and 6 % poleward of 51° (51p06). Two of the Northern Hemisphere cases (i.e., the 10 % – N61p10 – and 25 % – N71p25 – reductions) are the same as the Arctic61_0.37 and Arctic71_0.37 simulations of Caldeira and Wood (2008). The indicated reductions for each hemisphere were chosen by Caldeira and Wood (2008) because, for their simulations, the effect was to roughly counter-balance Arctic warming from a doubling of the CO_2 concentration in the specified domain. A simulation was also run with a uniform, global 1.8 % TOA reduction in solar radiation (GSRM). To examine the quasi-equilibrium response, each simulation was carried out for 100 model years, with the first 40 yr discarded and the last 60 yr used in the analysis.

4 Temperature and precipitation responses to the reductions in solar radiation

The upper left panel of Fig. 1a shows the calculated warming for a CO_2 doubling. Starting from this initial condition, the top center panel shows the atmospheric cooling near the surface that would result from a 1.8 % reduction in global solar radiation

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(run GSRM), and the top right panel shows the remaining warming compared to the $1 \times CO_2$ baseline. Figure 1b shows the warming due to the CO_2 doubling that is not counter-balanced by the imposed global solar reductions. As for all maps presented, the shading indicates areas where the changes are not statistically significant at the 95 % confidence level. To first order, the cooling shown for the GSRM simulation is amplified in polar regions and the pattern and magnitude of the response are similar, but opposite in sign, to the increase in temperature from a CO_2 doubling ($2 \times CO_2$).

The lower nine panels of Fig. 1a and b show the comparable model results for the three latitudinal ranges of solar reductions in each hemisphere (left and center columns) and for the hemispheres together (right column). As expected, the temperature changes induced by the polar solar-reduction simulations are largest in the hemisphere where the reductions are imposed. The combined effects of the solar reduction and ice-albedo feedback created a larger polar amplification for the polar reduction cases than for the global reduction.

The induced surface coolings in the polar reduction simulations are not confined to the polar regions. For example, the solar reductions applied simultaneously to the high latitudes of the Northern and Southern Hemispheres resulted in decreases in surface air temperature that were statistically significant over most of the world. Even the single-hemisphere reduction simulations indicated there would be distant effects; for example, the Southern Hemisphere reductions resulted in a small cooling over some areas of the Northern Hemisphere as well as the Arctic Ocean, and the Northern Hemisphere reductions caused a statistically significant temperature decrease over the Amazon.

Except for the S71p25 simulation, where the very reflective Antarctic ice sheet underlies virtually the whole area where the solar reduction is imposed (thus reducing the effect of the solar reduction), the global response does not appear to be sensitive to the latitudinal extent of the solar radiation reduction (see Table 1). While the strengths of the solar reductions at the three different latitudes were chosen to lead to about the same global annual-average reduction in TOA solar insolation (0.37 % for the one-hemisphere reductions poleward of 71 and 61° and 0.44 % for the reductions

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poleward of 51°), the seasonal durations of sunlight and the areas of imposition and underlying surface characteristics are quite different and thus lead to different changes in absorbed solar radiation.

Figure 1b shows that, while significant reductions in annual-average temperature can be induced, none of the solar reduction simulations provides a perfect counter-balancing; this will likely be the case independent of the approach to climate engineering that might be considered. The global solar reduction does significantly counter-balance the CO_2-induced warming, except in high latitudes. Although significantly smaller in terms of the induced global-average reduction in solar radiation, the polar reductions appear to have the potential for moderating warming over much of the globe, even though imposed only over limited latitudinal and seasonal time periods.

Figures 2 and 3 show the responses of Northern and Southern Hemisphere sea ice, respectively. Not surprisingly, Arctic sea ice extent increases in response to the global and Northern Hemisphere reductions in solar radiation, but it also shows a small response to Southern Hemisphere solar reductions. In contrast, Antarctic sea ice responds only to the global and Southern Hemisphere solar reductions, with virtually no response to reductions in Northern Hemisphere solar radiation.

Figure 4 shows that the increases in sea ice caused changes in the annual cycle of the zonally averaged net radiative flux at TOA. The larger deficit in TOA radiation during each hemisphere's polar summer leads to an additional regional loss of energy and results in more energy being drawn poleward from low latitudes, thus amplifying the cooling outside the polar region where the solar reduction was imposed. In the $2 \times CO_2$ case, the net changes in high-latitude radiation were positive during summer (consistent with more energy being absorbed due to a reduced albedo from less extensive sea ice) and negative during winter (consistent with more energy being emitted due to the warmer polar regions, particularly from the Arctic). As expected, the solar reduction cases show the opposite changes occurring, with much less energy being absorbed in summer and less radiation being emitted in winter due to the colder conditions created

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when sea ice insulates the lower atmosphere from the heat held in the ocean waters below the sea ice.

In non-polar latitudes, the changes in net radiation are generally positive (i.e., indicating reduced IR emission to space), consistent with lower temperatures as a result of the solar reductions. Negative values, indicating increased outgoing radiation, are evident in relatively thin bands near the equator where the ITCZ shifted in latitude, generally moving away from the hemisphere where the solar reduction was imposed so that an increased area of tropical waters was available to warm and moisten the overlying air.

Figure 5 shows the annual cycle of changes in surface temperature for the various simulations. For the CO_2 doubling, polar regions warm most, with the warming greatest in their cold seasons. For the solar reduction simulations, the sign is reversed, the cooling being greatest in the polar regions and during the times with no or low sunlight. For the global solar reduction, the counter-balancing of the CO_2-induced temperature increase is generally closest at low latitudes and not as complete at high latitudes, reflecting the different seasonal and latitudinal patterns of forcing of greenhouse gases and solar radiation. For the polar reduction simulations, the hemisphere of the solar reduction shows the most significant cooling, with ocean thermal buffering spreading the cooling roughly evenly through the year at non-polar latitudes even though the solar reductions have a strong seasonal signal. For the case of solar reductions in both polar regions, the cooling effect is relatively even through the seasons, except in polar regions where the cooling is concentrated in the non-summer seasons as a result of the increased sea ice cover and its insulating effect on ocean waters (Robock, 1983).

Figure 6a shows the percentage changes in annual mean precipitation for a CO_2 doubling, and then for the counter-balancing effects of the solar-reduction simulations with respect to the CO_2-altered climate. The $2 \times CO_2$ simulation indicates that the statistically significant changes over land areas are concentrated in higher latitudes, with somewhat less confidence that the expansion of the subtropical dry zones may also be significant. The global solar reduction generates statistically significant results

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in essentially the same regions, but with opposite sign, leading to a near counter-balancing of precipitation changes, except for a slight northward shift in the ITCZ.

The polar reductions in solar radiation, which do not directly diminish the solar radiation in low and mid-latitudes that drives the global hydrological cycle, lead to somewhat different results. For these simulations, the areas of land for which there are statistically significant results generally increase as the latitudinal extent reaches toward mid-latitudes. For large areas in the mid and low-latitudes, however, the solar reductions do not have a noticeable moderating influence on the changes in precipitation, as shown in Fig. 6b, which shows the percentage precipitation changes after the joint influences of CO_2 doubling and solar reductions.

These results add nuance to the finding in Caldeira and Wood (2008) that polar reductions in solar radiation do not generally diminish the increase in high-latitude precipitation caused by the doubled CO_2 concentration – the more the solar reduction extends over latitudes where land surface heating is needed to drive the monsoon circulation and ocean surface heating to drive evaporation, the greater the effect on the hydrologic cycle. Conversely, the more the solar reduction can be limited to high latitudes (e.g., by how the reduction is accomplished), the less the effect on precipitation over mid-latitude regions. Recalling the earlier discussion of the effects on temperature, which showed very little dependence of the cooling effect on the latitudinal extent of the polar reduction, the different results for precipitation suggest the possibility of optimizing the pattern and extent of solar reductions in high latitudes so as to minimize the influence on mid-latitude precipitation patterns and storm tracks, at least based on these simulations of the steady-state response (Ban-Weiss and Caldeira, 2010).

In undertaking such an optimization, however, special attention would need to be paid to what is happening in low latitudes, where the polar reductions in solar radiation caused a meridional shift in the ITCZ that primarily affected precipitation over critical low-latitude areas. In particular, the southward shift of the ITCZ due to the northern high-latitude solar reductions projected a decrease in precipitation over the Sahara

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whereas the northward shift of the ITCZ due to the southern high-latitude reductions suggested a decrease over the Amazon.

Figure 7 shows the annual cycle of changes in precipitation for the various simulations. The most noticeable feature is the persistent latitudinal shift in the ITCZ, with the change being evident in the responses to global forcing (i.e., $2 \times CO_2$ and GSRM) as well as in the polar reduction simulations. The shift is evident in all seasons, being relatively stable through the year for the global reduction simulation, but, in the polar simulations, showing a seasonal shift away from the polar region where the solar reduction was imposed. The strength of the shifts varies, being strongest for the cases where the solar reduction extends further toward mid-latitudes (i.e., the magnitude of the change is greater for solar reductions reaching 51° than for those confined to poleward of 71°).

5 Relative effectiveness of the alternative solar reduction extents

In considering alternative approaches to climate engineering, especially an alternative to incrementing the global stratospheric sulfate layer, a measure of the relative effectiveness is needed. In our analyses, we normalize the temperature response for each simulation by calculating the global and regional sensitivities. The details of these calculations are described in Appendix A.

Figure 8 compares the global-scale sensitivities for each of the solar reduction simulations, specifically the normalized changes in global mean surface air temperature, TOA albedo for clear and all-sky conditions, ice fraction, and cloud fraction per unit change in radiative forcing. All of our solar-reduction simulations led to a decrease in surface air temperature and an increase in ice fraction that, in turn, led to an increase in the TOA clear-sky albedo. However, the cloud response in the simulations was dependent on the particular latitudinal extent of the reduction in solar radiation. In the globally uniform solar-reduction simulation, the increase in clear-sky albedo due to the

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increase in ice fraction was offset by a reduction in cloud fraction, such that the TOA all-sky albedo remained roughly unchanged.

In the northern high-latitude solar reductions, the all-sky albedo decreased because the decrease in cloud fraction was more than made up for by the increase in clear-sky albedo resulting from the increases in sea ice extent. In the southern high-latitude solar reductions, however, the cloud fraction increased along with the ice fraction, leading to an increase in all-sky TOA albedo. The increases in both cloud and ice fractions thus contributed to a higher climate sensitivity for the southern than for the northern high-latitude solar reductions.

Table 1 shows a comparison of the numerical results from the simulations, showing that the global climate sensitivity for the global solar reduction is roughly 0.5 K $(\mathrm{Wm}^{-2})^{-1}$, whereas the global climate sensitivities for the high-latitude solar reductions range from 0.7 to 1.7 K $(\mathrm{Wm}^{-2})^{-1}$. These values indicate a dependence on the underlying albedo and geography of the directly affected region. Primarily because of the strong response of Southern Ocean sea ice, the global climate sensitivity for southern-latitude solar reductions of roughly 1.5 K $(\mathrm{Wm}^{-2})^{-1}$ was about double that for northern solar reductions, even though the decreases in global mean temperature were similar. As indicated in the entries for the separate and combined northern and southern high-latitude solar reductions, the climate sensitivities for high-latitude solar reductions appear to be roughly additive (cf., Ban-Weiss and Caldeira, 2010), suggesting that solar reductions in different latitude bands might be linearly scalable to match the changing intensity of the greenhouse gas induced radiative forcing.

To determine the regional climate sensitivity (i.e., the normalized responses for the regions where the solar reduction was imposed), we calculated the change in the regional energy balance for the northern and southern solar reductions (see Appendix A). As indicated in Table 1, the S61p10 simulation (i.e., 10 % reduction in TOA solar insolation poleward of 61° S) exhibited the largest regional climate sensitivity (i.e., >4 K $(\mathrm{Wm}^{-2})^{-1}$ in this region). In contrast, the regional climate sensitivity for S71p25 was less than that for the similar northern forcing (i.e., N71p25). These hemispheric and

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latitudinal differences are associated with the differing land-ocean distributions and associated differences in surface albedo, as well as the different potential for spreading of sea ice and changes in cloud cover. In the Arctic, sea ice is confined mostly north of 70° N, although in winter it can reach toward ∼ 40° N in some regions.

Around Antarctica, however, sea ice extent can be present from ∼ 80° S to ∼ 60° S and could grow even further northward if conditions were cold enough, creating a very large feedback potential. The larger energy reduction in Southern Hemisphere regions led to a much greater increase in heat transport into the southern than northern regions of the solar reductions, the extra energy flow occurring because there are limits to the meridional temperature gradients that the atmosphere-ocean system can sustain. As a result, Southern Hemisphere solar reductions led to much greater cooling outside the polar region than for identical solar reductions in the Northern Hemisphere, with the southern reductions even causing some cooling in the Northern Hemisphere. With both the Northern and Southern Hemispheres sharing the excess solar energy that accumulates in the low-latitude oceans, however, the simulations with solar reductions in both hemispheres led to roughly similar latitudinal cooling in both hemispheres (see Fig. 5).

Figure 9 shows the changes in long-wave and short-wave radiation feedback and horizontal heat flux for the various simulations. Long-wave feedback is defined as the change in net long-wave radiation at the TOA, and the short-wave feedback as the change in net short-wave radiation at the TOA minus the imposed radiative forcing. For the globally uniform solar reduction, short-wave radiation feedback is relatively small because cloud and sea ice feedbacks tend to cancel out over the globe. Because this is an equilibrium simulation, long-wave radiation must change, recreating the energy balance at the TOA (consistent with a ratio of 1). For the high-latitude solar reduction cases, however, which consider only the changes within the region where the solar reduction is imposed, a local balancing of the terms need not result. In the polar regions, the positive short-wave feedback due mainly to increased sea ice extent is similar in magnitude to the long-wave feedback due to the insulating effects of increased sea ice

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extent. Because of the combined energy reduction that results, the meridional heat flux convergence must increase. Compared to the regional sensitivity in other regions, the high regional sensitivity for S61p10 resulted from the greater potential in this region for changes in sea ice extent, which increases the cooling in adjacent areas, making this region the most efficient location for solar reductions, at least in terms of induced temperature change.

6 Discussion

With our calculations indicating that solar reductions in each polar region can counter-balance at least some of the warming in the same hemisphere and that simultaneous reductions in both hemispheres can partially counter-balance global-scale warming, the potential emerges to adjust each hemisphere's solar reduction in magnitude, latitudinal pattern, and timing to generate an optimal counter-balancing effect.

That the counterbalancing effect could be of sufficient magnitude to be useful is confirmed by observational analyses reported by Miller et al. (2012), who explain that the cause of the Little Ice Age was likely two periods of major volcanic eruptions in the late-13th and mid-15th centuries. While they cite four very large volcanic eruptions as most important in reducing the effects of solar heating, they also indicate that relatively small reductions in solar radiation coupled with sea ice/ocean feedbacks can lead to significant summer cooling that can persist over decades.

While there is good understanding about why climate model simulations show a strong polar amplification in their temperature responses to increases in the relatively smooth latitudinal forcing caused by rising greenhouse gas concentrations (e.g., Meehl and Stocker, 2007), model studies also indicate that forcing applied in high latitudes is relatively more effective in altering the global average temperature than a globally uniform forcing. For example, studies by Forster et al. (2000) and Boer and Yu (2003) found that when CO_2 forcing was applied only to the extra-tropics (i.e., poleward of 30°), climate sensitivity was about 20 % higher than when the CO_2 forcing was applied

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uniformly around the globe. Consistent with these results and the results of Caldeira and Wood (2008), surface air temperatures in our simulations were more sensitive to insolation reductions over high latitudes than to comparable reductions imposed uniformly over the globe. Indeed, that the NS51p06 simulation produced very similar counter-balancing of temperature and precipitation changes to GSRM suggests that at least some of the unintended consequences of global solar reduction may be avoided by limiting the reductions to the two polar regions.

Solar reductions over high latitude regions may also be more feasible than global reductions because of the need to impose the reduction only over the few-month sunlit periods and over much smaller areas; that this increases the intensity of the reflection that must be created, however, could well be problematic.

For precipitation, the results are more complex. While the reduced temperatures led to a decrease in global precipitation, the precipitation increase in polar regions caused by CO_2-induced warming was only minimally moderated. With lower temperatures, a larger fraction of the precipitation would fall as snow; indeed, combining the cooling with the increased snowfall would be expected to contribute to rebuilding at least some of the disappearing mountain glaciers and ice sheets.

In considering the potential for using solar reductions in polar regions to return climatic conditions toward a cooler state (e.g., toward preindustrial conditions), caveats to this analysis must be noted. First, our analysis is based on equilibrium simulations and carried out using an atmospheric model atop a slab ocean. More definitive exploratory simulations will be needed using a full Earth system model that can examine the potential for counter-balancing gradual warming with gradually intensifying solar reductions.

Second, our simulations are idealized because they are based on simply reducing the amount of solar radiation rather than actually enhancing reflection of clouds and/or increasing aerosol loading by injection of a reflecting substance such as sulfate. Robock et al. (2008), using a global climate model with interactive stratospheric chemistry, carried out separate simulations comparing the temperature responses to

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stratospheric injections of SO_2 into the Arctic and tropical stratosphere. They concluded that the Arctic injection would lead to cooling as far south as 30° N and weaken the summer monsoons over Africa and Asia, just as was the case for tropical injections. The extent to which these lower latitude changes were due to the spread of sulfate aerosols out of the polar region, however, is not clear. This is a concern because their SO_2 injections extended through the full year, including through the polar night, thus increasing the likelihood that the sulfate could spread and overestimating the required injection amount by a factor of roughly 3. While our simulations make clear that the suppression of mid-latitude precipitation increases as the solar reductions extend from polar to lower latitudes, effectively confining the solar reduction to the polar regions might limit interference with precipitation systems in lower latitudes.

Despite the idealized aspects of our simulations, analysis of the nature and extent of the potential for polar injections to at least in part counter-balance the changes being brought on by the increasing concentrations of greenhouse gases suggests that further investigation is warranted. While some warming remains in our simulations for both the global and high-latitude solar reductions, appropriately adjusting the magnitude and extent of the various high-latitude solar reductions might, for example, make it possible to induce temperature reductions and precipitation shifts that would both promote regrowth of the sea ice cover and counteract mass loss from glaciers and ice sheets. With warming of the Southern Ocean being critical in loss of ice mass from Antarctic ice shelves (Pritchard et al., 2012), there is strong incentive to simultaneously seek to counterbalance warming in both hemispheres.

This is fortunate because, while solar reductions in one hemisphere appear to lead to a statistically significant shift in the ITCZ across the Indian and Pacific Oceans, combining suitable polar reductions in both hemispheres (e.g., with differing strengths and latitudinal extents in the two hemispheres) might also make it possible to limit this shift to a small residual of the southward shift resulting from a CO_2 doubling. That such adjustments in the ITCZ might be feasible is also suggested by idealized aqua-planet simulations conducted by Kang et al. (2008) using an atmospheric GCM coupled to a

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slab ocean. Those simulations investigated the consequences of an imposed heating in the extratropics, finding that the ITCZ shifted poleward into the warmed hemisphere.

Hansen et al. (1997) reported a similar result in a study in which they applied a "ghost forcing" separately to the Northern and Southern Hemispheres. They calculated a climate sensitivity of 0.63 K $(\mathrm{Wm}^{-2})^{-1}$ for their northern forcing and of 0.80 K $(\mathrm{Wm}^{-2})^{-1}$ for their southern forcing. When they applied the forcing only to the extra-tropics poleward of 30°, this difference between the northern and southern forcings increased (i.e., 0.65 K $(\mathrm{Wm}^{-2})^{-1}$ for the northern extra-tropical forcing versus 0.96 K $(\mathrm{Wm}^{-2})^{-1}$ for the southern extra-tropical forcing).

Several paleo-climate simulations have also indicated that the ITCZ moved southward during the Last Glacial Maximum when the Northern Hemisphere was more strongly cooled than the Southern Hemisphere (Koutavas and Lynch-Stieglitz, 2004; Broccoli et al., 2006). Although the forcing in those studies was imposed on the surface or in an ocean mixed layer, the TOA forcing in our simulations imposed also resulted in a poleward shift of the ITCZ toward the warmer (or unperturbed) hemisphere.

The greater response of the sea-ice extent (and thus the larger albedo change) resulting from the southern high-latitude solar reduction is also in accord with previous findings. For example, Hall (2004) found that surface-albedo feedback accounts for about 50 % of the warming in high latitudes and is larger in the Southern Hemisphere than in the Northern Hemisphere. Winton (2005) confirmed this result using results from the Coupled Model Intercomparison Project (CMIP3), although the simulated surface warming was greater in the northern high latitudes than in the southern high latitudes because of differences in heat capacity and changes in albedo, strength of the low-lying inversion, and other feedback processes (Winton, 2006).

While our study points out the importance of changes in the extent of Southern Ocean sea ice in determining the regional and global climate response, high confidence cannot be placed in the quantitative response because our simulations were limited by having fixed ocean energy transport and use of a thermodynamic sea ice model. Nevertheless, our study demonstrates that different regions may respond very

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differently to differences in applied forcing, and these within-region differences can have different consequences for the remainder of the planet.

7 Summary and next steps

Our model simulations indicate that reductions in solar radiation in polar regions can both limit warming in the regions where the reductions are imposed while also helping to moderate the temperature increase in lower latitudes. In addition, because the polar reductions do not significantly reduce the increase in high-latitude precipitation caused by the increasing greenhouse gas concentrations, there is the potential to moderate and even reverse the mass loss from glaciers and ice sheets. With the rate of sea level rise apparently accelerating, rebuilding the polar land ice could benefit coastal and island nations around the world by slowing or reversing this cryospheric contribution to sea level.

Were solar reductions in polar regions to actually be considered, the pattern and degree of deployment would likely involve different extents and intensities in each hemisphere. In the Northern Hemisphere, solar reductions north of the Arctic Circle appear capable of generating a significant temperature offset without substantial diminution of solar radiation or whitening of the sky over lower latitudes. In the Southern Hemisphere, because of its low albedo and the potential for stimulating growth of sea ice, reducing solar radiation over the Southern Ocean, for example by brightening clouds, would be much more effective than reducing it over the highly reflective Antarctica ice sheet. Limiting the reductions in this way, as well as possibly using different reduction techniques in each hemisphere, might well help to reduce unintended impacts on the stratospheric ozone layer and on Antarctic astronomical observations.

While our simulations have provided a number of initial insights, a more comprehensive research effort is needed to develop a broader and deeper understanding of the processes that determine the high latitude climate response and potential for counterbalancing warming over the rest of the Earth. In particular, simulations are needed that

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consider the implications and consequences of plausible approaches for actually reducing solar absorption. Beyond our equilibrium simulations, simulations are needed in which solar reductions are applied with gradually increasing intensity and the consequences both inside and outside the directly affected regions are compared to the consequences resulting from the projected increases in greenhouse gas concentrations without climate engineering. Such increased understanding has the potential to provide a richer base of information and set of choices for policymakers to evaluate in seeking to limit the consequences of global climate change.

Appendix A

Estimation of global and regional climate sensitivity

Because the system as a whole starts responding as soon as the simulation starts, it is not possible to use the conventional definition for radiative forcing (IPCC, 1994). In its place, we calculate the "instantaneous radiative forcing" (IRF), defined as the change in the TOA energy balance at the start of the simulation. The instantaneous radiative forcing at a local point i (F_i) due to the reduction in solar insolation can be estimated from

$$F_i = (1 - \alpha_i)\,\Delta S_i, \tag{A1}$$

where α_i is the local TOA albedo from the $2 \times CO_2$ control simulation and ΔS_i is the change in solar insolation at TOA per unit surface area relative to the control simulation. F can be integrated over the globe and divided by the global surface area to obtain global mean instantaneous radiative forcing.

The global mean climate sensitivity to the IRF is then obtained by dividing the change in global mean surface air temperature by the global mean IRF. For simulations in which solar insolation is changed, the IRF is likely to be nearly the same as the adjusted radiative forcing as conventionally defined to include stratospheric adjustment. This near

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similarity results because stratospheric adjustment in the case with added greenhouse gases is primarily the result of the increased emissivity induced in the stratosphere, whereas the adjustment does not occur for simulations with reduced solar insolation. Recognizing this, we use the term “radiative forcing” in this paper instead of IRF. Using the global mean IRF ($\overline{F}$), the global climate sensitivity is thus given by

$$\overline{F} = \lambda \overline{T} \tag{A2}$$

where $\Delta\overline{T}$ is the change in global mean surface air temperature. With this formulation, λ is the global climate response parameter and its inverse is defined as the global climate sensitivity.

We also calculated the regional climate sensitivity for the regions where solar insolation was reduced. In calculating this sensitivity, we included consideration of horizontal energy transport, as was done by Boer and Yu (2003). Whereas Boer and Yu (2003) were successful in using the change in meridional temperature gradient to estimate changes in the energy transport, the situation is more complex with a warming climate. Under such conditions, although the meridional gradient in temperature decreases, the atmospheric poleward energy transport is projected by models to increase due to an increase in sensible energy transport in low latitudes and an increase in latent energy transport in middle and high latitudes (Held and Soden, 2006).

Our analysis of regional climate sensitivity therefore accounts directly for calculated changes in atmospheric meridional energy transport, especially transport into the different high latitude regions where solar insolation is decreased. Doing this required that account be taken of the effects of changes in meridional energy fluxes as well as the imposed reduction in solar radiation. To calculate the meridional energy transport (ΔH_φ) at latitude φ, we ignored changes in annual-mean atmospheric energy storage and then integrated the net horizontal energy flux from the surface to the top of the atmosphere from the pole to the boundary latitude for each of the regional solar reductions. To eliminate spurious, non-zero energy transports at the poles, the global average of the net energy flux was subtracted uniformly at all latitudes. Because ocean

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energy transport is held fixed for the model configuration that we use, we only took the changes in atmospheric meridional energy transport into account for this analysis. The radiative forcing averaged at latitude φ will thus follow the relationship (Murphy, 2010):

$$F_{\varphi} = \lambda_{\varphi} \Delta T_{\varphi} + \Delta H_{\varphi}, \tag{A3}$$

where λ_{φ} is the climate response parameter for the region and ΔT_{φ} is the change in the region's mean surface air temperature relative to the $2 \times CO_2$ control run. The regional climate sensitivity is then defined to be the inverse of λ_{φ}.

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Table 1. Global and regional mean reductions in solar insolation and climate sensitivity for the various perturbation simulations. The baseline simulation with doubled CO_2 had a concentration of 560 ppm and a solar constant of 1366 Wm^{-2}. Details of the calculations of climate sensitivity are described in Appendix A.

Simulations with 560 ppm CO_2 and specified reduction in solar insolation	Amount of reduction in solar insolation and the region where the reduction was applied	Instantaneous reduction in top-of-atmosphere solar forcing (Wm^{-2}), positive downward		Climate sensitivity [K $(Wm^{-2})^{-1}$]	
		Global average	Average over the region where the forcing was applied	Global sensitivity	Sensitivity within the region where the forcing was applied
Global solar radiation management (GSRM) simulation					
GSRM	1.8 % uniformly over the entire globe	−4.14	−4.14	0.49	0.49
Northern high-latitude forcing simulations					
N51p06	6 % over the latitudes north of 51° N	−0.77	−6.86	0.69	1.45
N61p10	10 % over the latitudes north of 61° N	−0.57	−9.05	0.69	1.91
N71p25	25 % over the latitudes north of 71° N	−0.52	−19.07	0.76	1.77
Southern high-latitude forcing simulations					
S51p06	6 % over the latitudes south of 51° S	−0.75	−6.70	1.41	1.77
S61p10	10 % over the latitudes south of 61° S	−0.53	−8.41	1.65	4.27
S71p25	25 % over the latitudes south of 71° S	−0.43	−15.59	1.49	1.05
Northern and southern high-latitude forcing simulations					
NS51p06	6 % over the latitudes north of 51° N and south of 51° S	−1.51	−6.78	1.03	1.53
NS61p10	10 % over the latitudes north of 61° N and south of 61° S	−1.09	−8.73	1.14	2.51
NS71p25	25 % over the latitudes north of 71° N and south of 71° S	−0.94	−17.33	1.08	1.28

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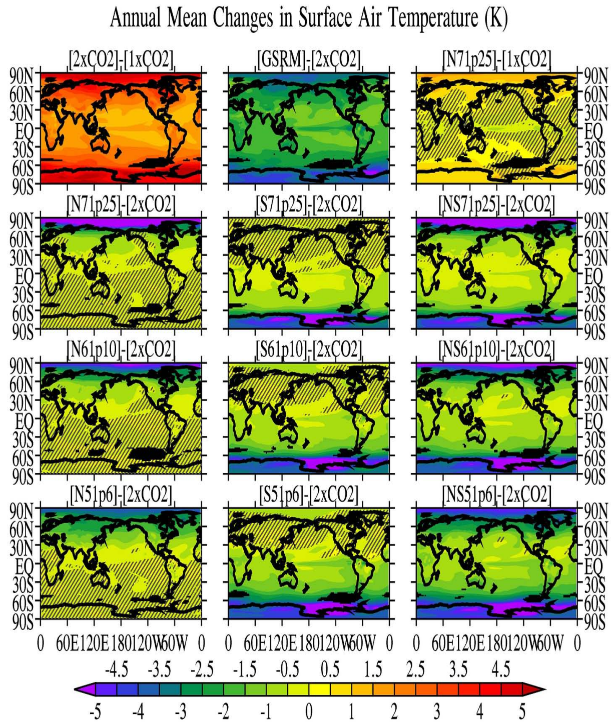

Fig. 1. **(a)** Changes in climatological annual-mean surface air temperature (in Kelvins) in response to specified changes in radiative forcing. The top row shows, left to right, the temperature increase for $2 \times CO_2$ as compared with $1 \times CO_2$, the temperature decrease from the $2 \times CO_2$ baseline with a globally uniform insolation reduction of 1.8 %, and the temperature change from the $1 \times CO_2$ baseline after a CO_2 doubling and 1.8 % reduction in solar insolation. The nine lower maps show the cooling resulting from reductions in TOA solar insolation as compared to the equilibrium temperature increase for a CO_2 doubling in the polar regions of the Northern (left column), Southern, (center) and both (right) Hemispheres. The second, third, and fourth rows show results for reductions in solar radiation extending from the pole to 71, 61, and 51° latitude, respectively. The hatching indicates areas where the changes are not statistically significant changes at the 95 % confidence level using a modified Student-t test for auto-correlated data (Zwiers and von Storch, 1995); areas with total efficient number less than 30 are blacked out because more sophisticated analysis is needed (see Zwiers and von Storch, 1995).

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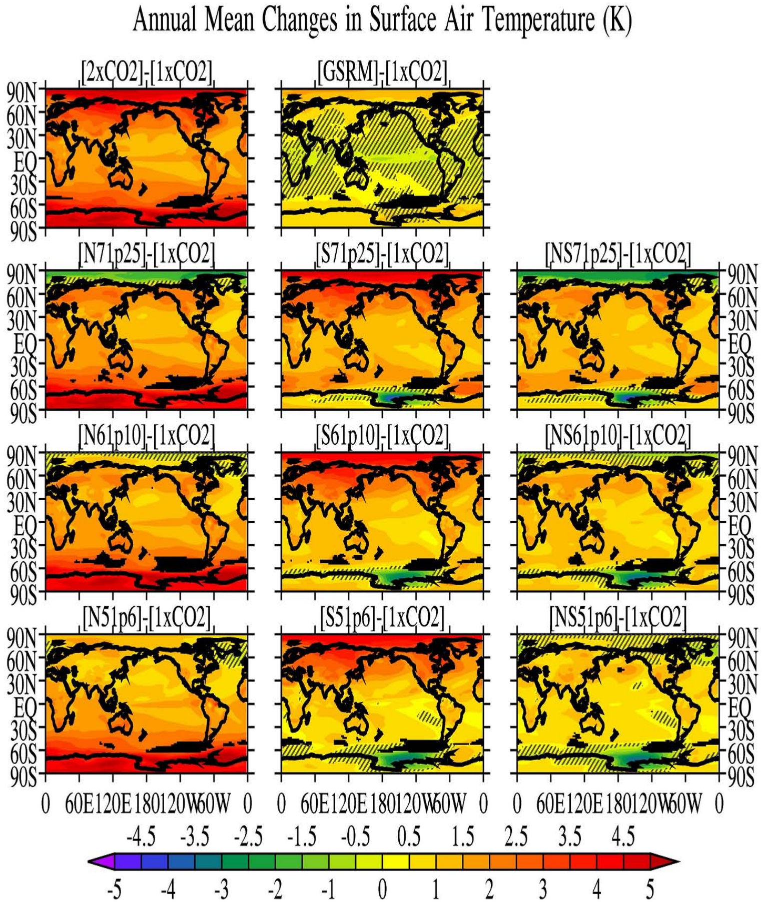

Fig. 1. (b) As for **(a)**, except annual-mean changes in surface air temperature are calculated from the 1 × CO_2 baseline after imposing both a doubling of the atmospheric CO_2 concentration (2 × CO_2) and the indicated reductions in TOA solar insolation. Units are Kelvins.

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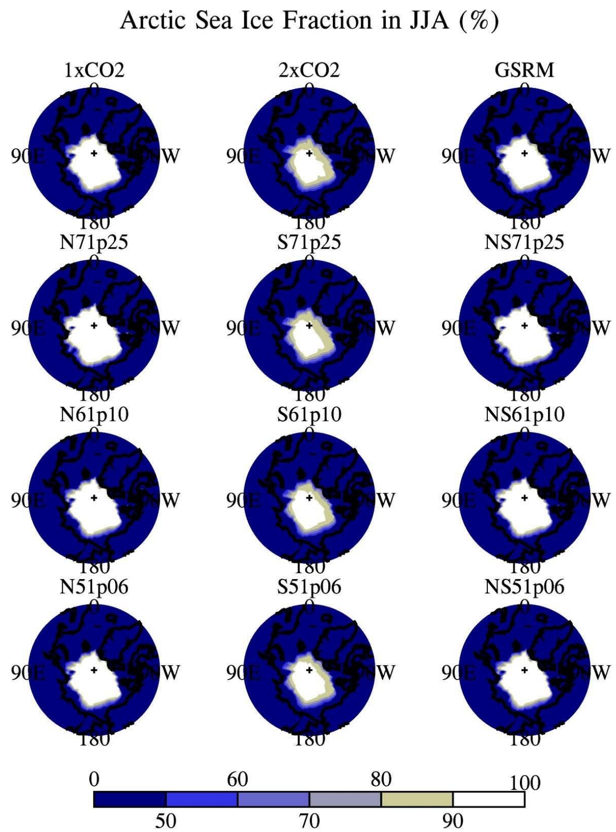

Fig. 2. Climatological mean sea ice fraction in the Arctic during June-July-August. The top row shows results for $1 \times CO_2$, $2 \times CO_2$, and for both a CO_2 doubling and a globally uniform reduction in insolation of 1.8%. The nine lower maps show the results for solar reductions in the polar regions of the Northern (left column), Southern, (center) and both (right) Hemispheres. The second, third, and fourth rows show results for solar reductions extending poleward from 71, 61, and 51° latitude, respectively. Units are percent.

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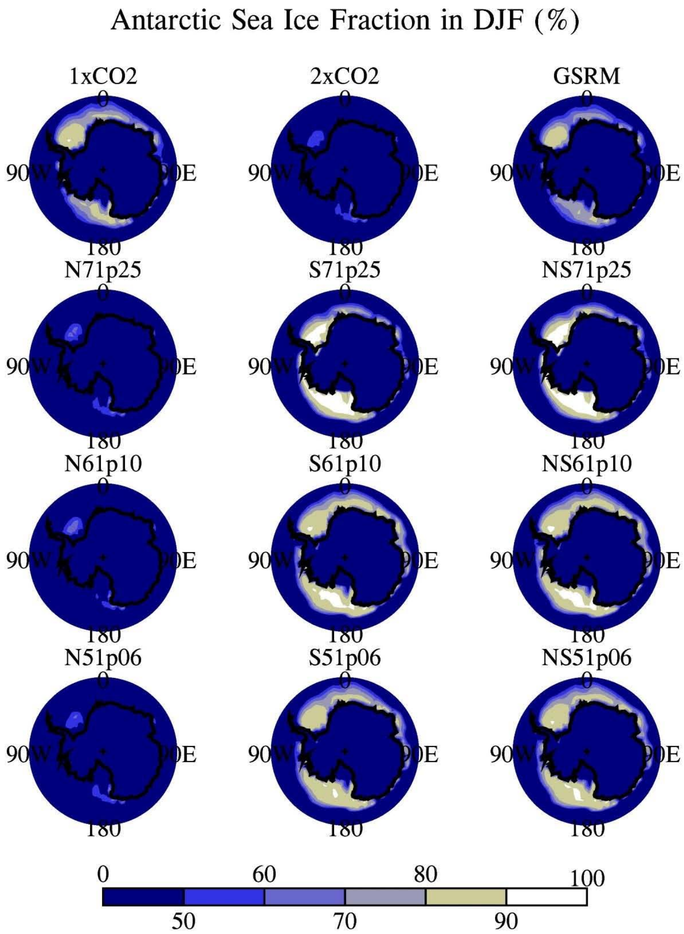

Fig. 3. Climatological mean sea ice fraction in the Antarctic during December-January-February. The distribution of maps is as in Fig. 2. Units are percent.

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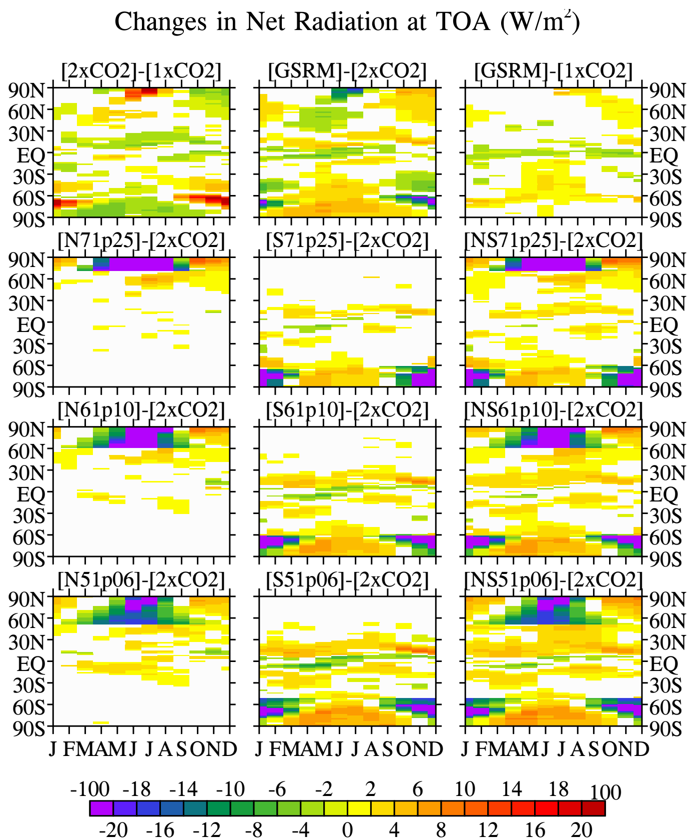

Fig. 4. Annual cycle of changes in net radiation at TOA due to the imposed reduction in TOA insolation as compared with $2 \times CO_2$. The distribution of maps is as in Fig. 1. Only the areas with changes statistically significant at the 95 % confidence level are shown in color. Units are in petawatts (PW).

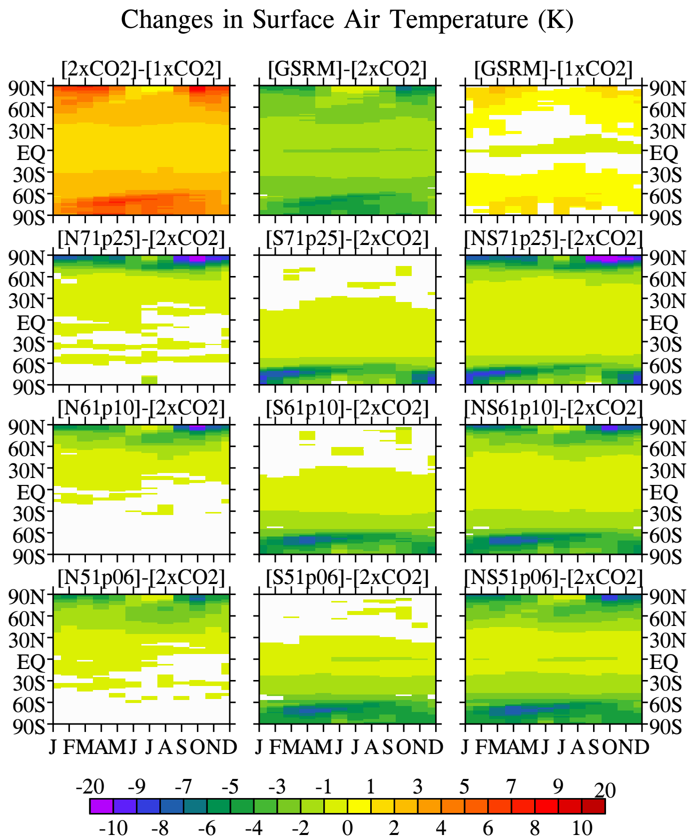

Fig. 5. Annual cycle of changes in surface air temperature due to reductions in TOA insolation as compared with 2 × CO_2. The distribution of maps is as in Fig. 1. Only the areas with results statistically significant at the 95 % confidence level are shown in color. Units are in Kelvins.

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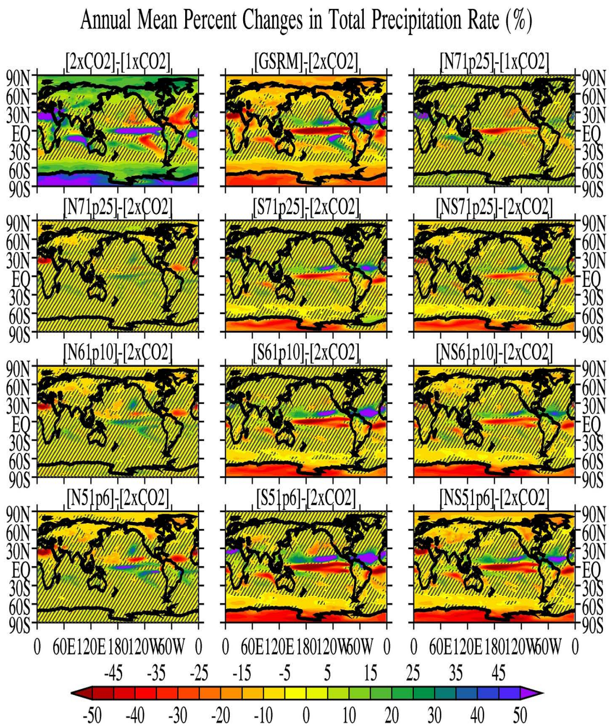

Fig. 6. (a) Percent changes in climatological annual-mean total precipitation rate at the surface due to specified reductions in TOA solar insolation as compared to the equilibrium changes that would result from a CO_2 doubling. The top row shows the changes in $2 \times CO_2$ as compared with $1 \times CO_2$ and the effects of a globally uniform reduction in insolation of 1.8 %. The nine lower maps show the percent changes for the polar solar-reduction simulations as compared to the with $2 \times CO_2$. Areas that are hatched are not statistically significant at the 95 % confidence level.

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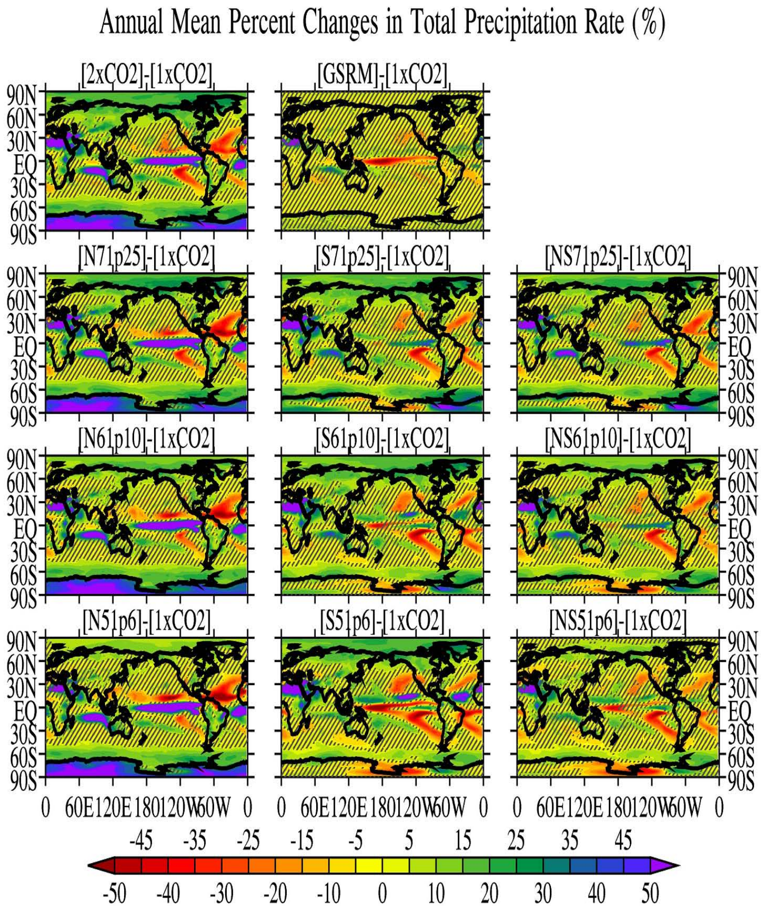

Fig. 6. (b) As for **(a)**, except for percentage changes in annual-mean surface precipitation rate from the 1 × CO_2 baseline after imposing both a doubling of the atmospheric CO_2 concentration (2 × CO_2) and the indicated reductions in TOA solar insolation.

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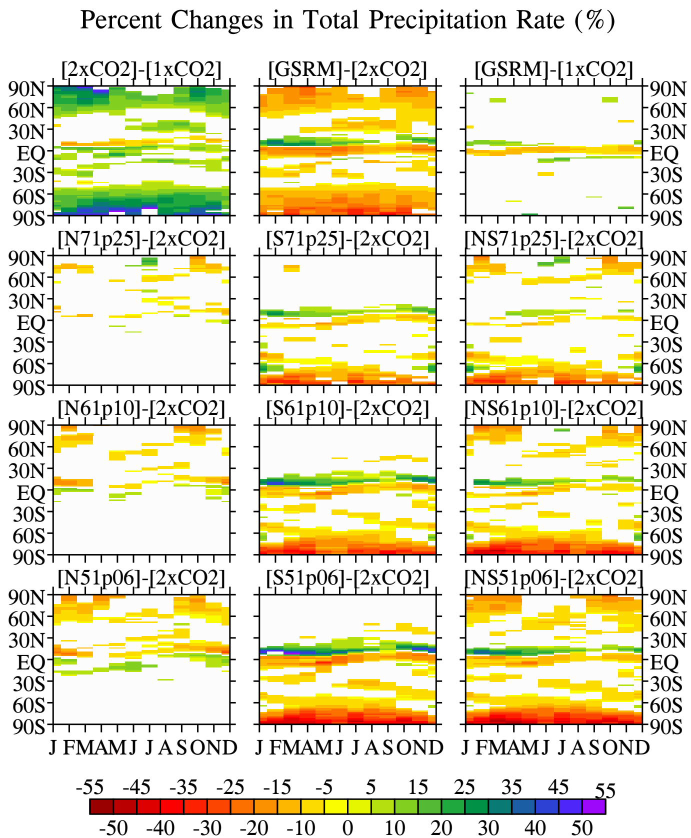

Fig. 7. Annual cycle of changes in total precipitation rate (in percent) at the surface due to reductions in TOA insolation as compared with $2\times CO_2$. The change for the $2\times CO_2$ case and the effect of a globally uniform reduction in insolation of 1.8 % as compared with $1\times CO_2$ case are also shown in the upper left and right corners as a reference. Only the areas with statistically significant changes at the 95 % confidence level are shown in color.

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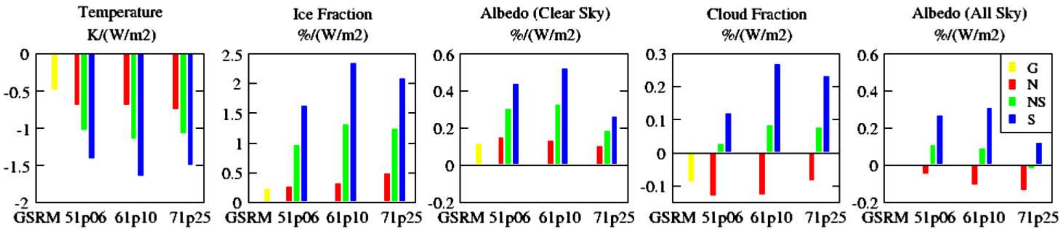

Fig. 8. Global mean changes in surface air temperature, ice fraction, TOA albedo for clear skies, cloud fraction, and TOA all-sky albedo, with each having been normalized by dividing by the reduction in solar forcing averaged over the entire globe. The yellow bars represent the results from the globally uniform reduction in solar insolation (G), the red bars from the northern high-latitude insolation reduction (N), the blue bars from the southern high-latitude insolation reduction (S), and the green bars from combined northern and southern high-latitude solar reduction (NS). For the three high-latitude reduction cases, incident solar radiation at the TOA was reduced by 6 % poleward of 51°, 10 % poleward of 61°, and 25 % poleward of 71°.

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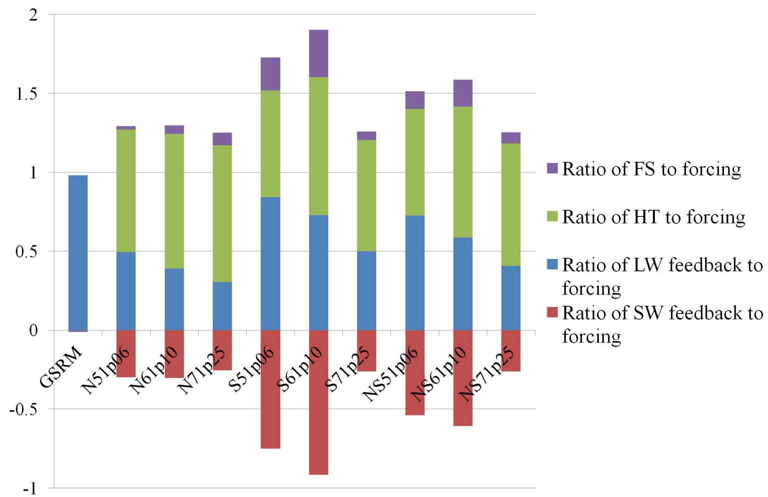

Fig. 9. Changes in the atmospheric energy balance in the region where the solar reduction was imposed, normalized by the region's reduction in short-wave radiative forcing. The terms shown are for the net change in the surface-to-atmosphere heat flux (FS), the atmospheric horizontal heat flux into the region (HT), the net long-wave energy flux (LW), and the net change in short-wave radiation (SW).

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