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Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO_2

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Abstract

It has been suggested that climate change induced by anthropogenic CO_2 could be counteracted with geoengineering schemes designed to diminish the solar radiation incident on Earth's surface. Though the spatial and temporal pattern of radiative forcing from greenhouse gases differs from that of sunlight, it was shown in a recent study that these schemes would largely mitigate regional or seasonal climate change for a doubling of the atmospheric CO_2 content. Here, we examine the ability of reduced solar luminosity to cancel the effects of quadrupling of CO_2 content. In agreement with our previous study, geoengineering schemes could markedly diminish regional and seasonal climate change. However, there are some residual climate changes: in the geoengineered $4 \times CO_2$ climate, a significant decrease in surface temperature and net water flux occurs in the tropics; warming in the high latitudes is not completely compensated; the cooling effect of greenhouse gases in the stratosphere persists and sea ice is not fully restored. However, these residual climate changes are much smaller than the change from quadrupling of CO_2 without reducing solar input. Caution should be exercised in interpretation because these results are from a single model with a number of simplifying assumptions. There are also many technical, environmental and political reasons not to implement geoengineering schemes.

Keywords: anthropogenic CO_2; climate change; geoengineering; mitigation of climate change

1. Introduction

Several schemes have been proposed to counteract the warming influence of increasing atmospheric CO_2 content by means of intentional manipulation of Earth's radiation balance (Budyko, 1977; Early, 1989; Seifritz, 1989; National Academy of Sciences, 1992; Watson et al., 1995; Flannery et al., 1997; Teller et al., 1997). These 'geoengineering' schemes typically involve placing reflectors or scatterers in the stratosphere or in orbit between the Earth and Sun at L1 Lagrange point, diminishing the amount of solar radiation incident on Earth. However, the temporal and spatial pattern of long-wave radiative forcing from increased atmospheric carbon dioxide (Kiehl and Briegleb, 1993) differs significantly (Fig. 1) from that of a change in effective solar luminosity (List, 1951). For example, carbon dioxide traps heat in both day and night over the entire globe with little meridional and seasonal variations, whereas diminished

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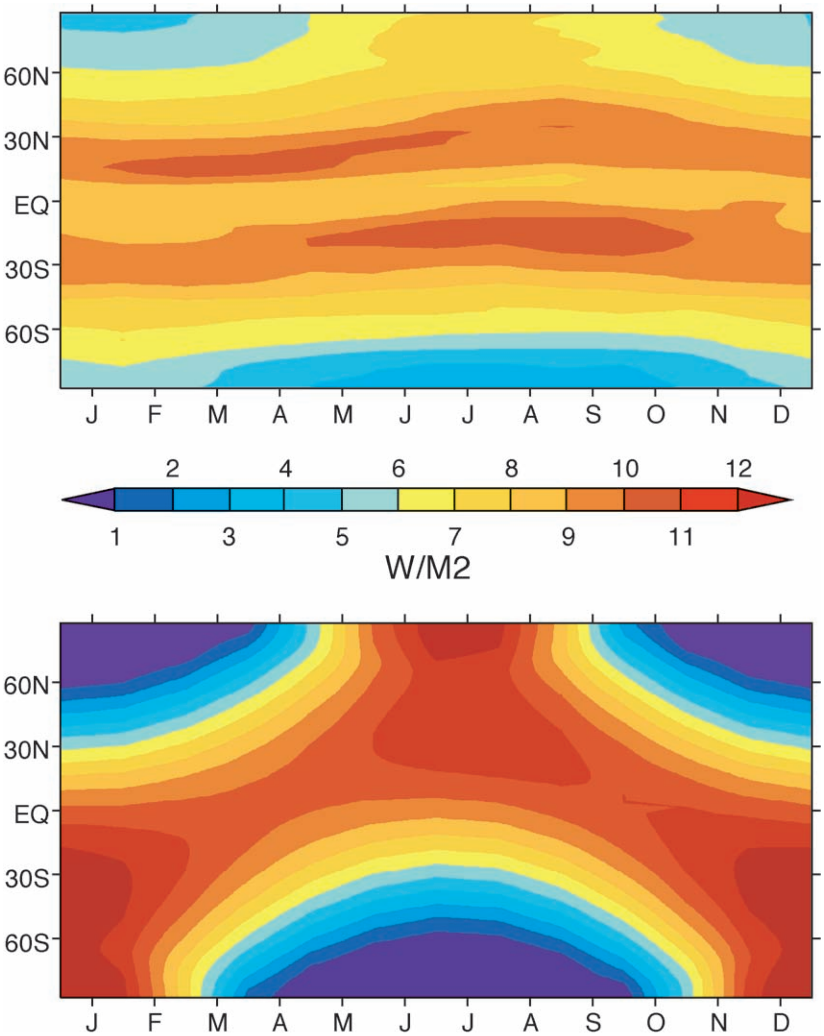

Fig. 1. Change in net long-wave radiative flux at the tropopause when CO_2 is quadrupled (top panel) with respect to the Control case and the reduction in incoming solar radiation (bottom panel) needed to compensate this forcing. Both values (W m^{-2}) are zonally averaged as a function of time of year. Change in solar radiation has a latitudinal and seasonal pattern markedly different from the radiative forcing of CO_2.

solar radiation would be experienced exclusively in daytime, and on the annual mean most strongly at the equator, and seasonally in the high-latitude summers (Fig. 1). Hence, there is little a priori reason to think that a reduction in the solar luminosity incident on the Earth would effectively cancel CO_2-induced climate change at all latitudes and seasons (Schneider, 1996). One might expect, on the basis of the considerations above, that a geoengineered CO_2-laden world would have less of a diurnal cycle, less of a seasonal cycle and less of an equator-to-pole temperature gradient than would have existed in the absence of human interference in the climate system. Such changes, even in the absence of globally and annually averaged warming, could produce damaging regional and seasonal climate change.

In a recent study (Govindasamy and Caldeira, 2000), it was shown that the geoengineering schemes that reduce the incident solar radiation uniformly by ~ 1.8% would largely mitigate global and annual mean climate change for a doubling of atmospheric CO_2 content from preindustrial levels. They further showed that such a reduction in solar luminosity would also largely compensate the regional or seasonal climate change. Since climate system has many nonlinear feedbacks, its behavior can be difficult to predict without careful modeling. It can be inferred from Kothavala et al. (1999) that the climate sensitivity—the change in global mean surface temperature per unit change in CO_2-induced radiative forcing—of the modeled climate system (CCM3) increases with increasing amounts of CO_2 content. Therefore, it is unclear if reducing solar luminosity could effectively cancel effects of larger increases in the atmospheric CO_2 content. In this paper, we investigate the effectiveness of these schemes in mitigating the global, regional and seasonal CO_2-induced climate change at four times the CO_2 content at preindustrial levels. We find that the compensation is not exact and there are some significant residual climate change, such as reduced surface temperatures and net surface water flux in the tropics in the geoengineered $4 \times CO_2$ world. Nevertheless, these residual climate changes are everywhere much smaller than the change from the quadrupling of CO_2 alone.

Caution should be exercised in interpreting our results because we have performed equilibrium climate simulations using a single atmospheric general circulation model coupled to a mixed layer ocean model. Our model does not have realistic transient forcing due to greenhouse gases and it lacks a sophisticated ocean model. It also lacks the feedbacks associated with land and ocean biosphere. It is possible that other atmospheric GCMs coupled to a full, three-dimensional ocean and carbon models and subjected to transient forcing would yield qualitatively and quantitatively different results (Hansen et al., 1999). Climate models exhibit a wide range of response for similar climate forcings (Hansen et al., 1997) and results may be highly sensitive to the formulation of the model and the parameterization of various physical processes (Hansen et al., 1999).

2. The general circulation model

We adopted Version 3 of the Community Climate Model (CCM3) developed at the National Center for Atmospheric Research (Kiehl et al., 1996). This is a spectral model with 42 spherical harmonics to represent the horizontal structure of prognostic variables: the horizontal resolution is approximately 2.8° in latitude and 2.8° in longitude. The model has 18 levels in the vertical. An important aspect of CCM3 is that it has very little systematic bias in the top-of-atmosphere and surface energy budgets. We adopted a version of the model with a simple slab ocean-thermodynamic sea ice model, which allows for a simple interactive surface for the ocean and sea ice components of the climate system. The slab ocean model employs a spatially and temporally prescribed ocean heat flux and spatially prescribed mixed layer-depth, which ensures replication of realistic sea surface temperatures and ice distributions for the present climate.

3. The experiments

We performed three model simulations: (i) “Control” or preindustrial, with a CO_2 content of 280 ppm and a solar “constant” of 1367 W m^{-2}; (ii) “$4 \times CO_2$”, with quadrupled atmospheric CO_2 content (1120 ppm) from the preindustrial levels, but the same solar “constant” as the Control simulation; and (iii) “Geoengineered $4 \times CO_2$”, with four times atmospheric CO_2 content and the solar “constant” reduced by 3.6%. The reduction in solar luminosity in (iii) was chosen to approximately offset the global and annual mean radiative forcing from a CO_2 quadrupling in this model (8.34 W m^{-2}), taking into consideration the model’s planetary albedo. In practice, this reduction in solar radiation incident on the Earth could be effected through the placement of reflecting or scattering devices between the Earth and Sun (Early, 1989; Seifritz, 1989; Flannery et al., 1997; Teller et al., 1997). At high latitudes, the resulting change in seasonal amplitude of insolation is about five times smaller than that associated with Milankovitch cycles (Imbrie et al., 1984).

Typically, the model needs to run for ~20 years to reach equilibrium. For the experiments presented here, the model was run for 40 years and the climate statistics presented below are the averaged values over the last 15 years of model simulations. We computed the difference in the mean results for a variety of quantities between the test (“$4 \times CO_2$” or “Geoengineered $4 \times CO_2$”) and Control simulations. Internal variability in the simulated climate introduces some noise into each simulation; therefore, we assessed the statistical significance of the difference in the means at each model-grid point using the Student's *t*-test (Chervin and Schneider, 1976a,b; Press et al., 1989), corrected for the influence of serial correlation (Zwiers and Storch, 1995).

4. Results

4.1. Global mean changes

Comparison of annual and global mean results (Table 1) suggests that the reduction in solar luminosity in "Geoengineered 4 × CO_2" largely compensates for the climatic impacts of increased CO_2 concentrations on surface temperature, absorbed surface radiative flux, precipitation, precipitable water vapor and sea ice volume. In the "4 × CO_2" simulation, the planet warms 4.02 K, leading to a reduction in sea ice volume and an increase in precipitation and precipitable water vapor. Other models with higher sensitivity and a dynamic ocean model may not necessarily reproduce this compensation. In order to compare the climate changes at different levels of CO_2, we show the annual and global mean quantities for the "2 × CO_2" simulation (Govindasamy and Caldeira, 2000). In the "2 × CO_2" simulation, the surface temperature increased by 1.75 K from the Control simulation, whereas it increases by 2.27 K from "2 × CO_2" simulation to "4 × CO_2" simulation. The last two rows in Table 1 indicate larger changes in global mean quantities for the climate change from "2 × CO_2" to "4 × CO_2" than for the change from Control to "2 × CO_2". Radiative forcing is the same for a doubling of CO_2 ("1 × CO_2" to "2 × CO_2" or "2 × CO_2" to "4 × CO_2") because of its logarithmic dependence on CO_2 concentration. This suggests that the climate sensitivity increases as the climate warms in this model presumably due to some positive feedbacks. The annual and global mean surface temperature shows a similar increase in climate sensitivity at higher concentrations of CO_2 (and hence, warmer climates) in a recent modeling study using CCM3 by Kothavala et al. (1999).

The 3.6% reduction in solar luminosity cools the Earth 4.09 K from its "4 × CO_2" state, slightly overcompensating the change due to CO_2 quadrupling (Table 1). Though the global mean surface temperature rise in "4 × CO_2" is almost exactly balanced in "Geoengineered 4 × CO_2", there are some residual changes in other quantities like absorbed surface radiative flux, precipitation, precipitable water and sea ice volume (Table 1). These global mean quantities except sea ice suggest a slightly colder "Geoengineered 4 × CO_2" planet than the control. The decrease in sea ice is due to a slight residual warming in high latitudes in the "Geoengineered 4 × CO_2". This result is expected, since the radiative forcing due to quadrupling of CO_2 in winter exceeds that due to the reduction in solar luminosity at high latitudes.

4.2. Surface temperature change

Comparison of results for annual mean surface temperature (Fig. 2) indicates that geoengineering may largely compensate for impact of increased CO_2 concentrations, despite the differences in the spatial pattern of radiative forcing between changes

Table 1
Annual and global means of surface temperature, total absorbed long-wave and short-wave fluxes at the surface, precipitation, precipitable water vapor and sea ice volume for the three simulations described in the text

Case	Surface temperature (K)	Absorbed radiative flux ($W\ m^{-2}$)	Precipitation (mm/day)	Precipitable water vapor (mm)	Sea ice volume ($\times 10^{12}\ m^3$)
Control	285.50	492.85	2.98	24.9	51.2
2 × CO_2	287.25	503.42	3.07	28.0	38.7
4 × CO_2	289.52	517.46	3.21	32.4	20.6
Geoengineered 4 × CO_2	285.43	488.70	2.88	23.7	48.8
2 × CO_2 – Control	1.75	10.57	0.09	3.1	– 12.5
4 × CO_2 – 2 × CO_2	2.27	14.04	0.14	4.4	– 18.1

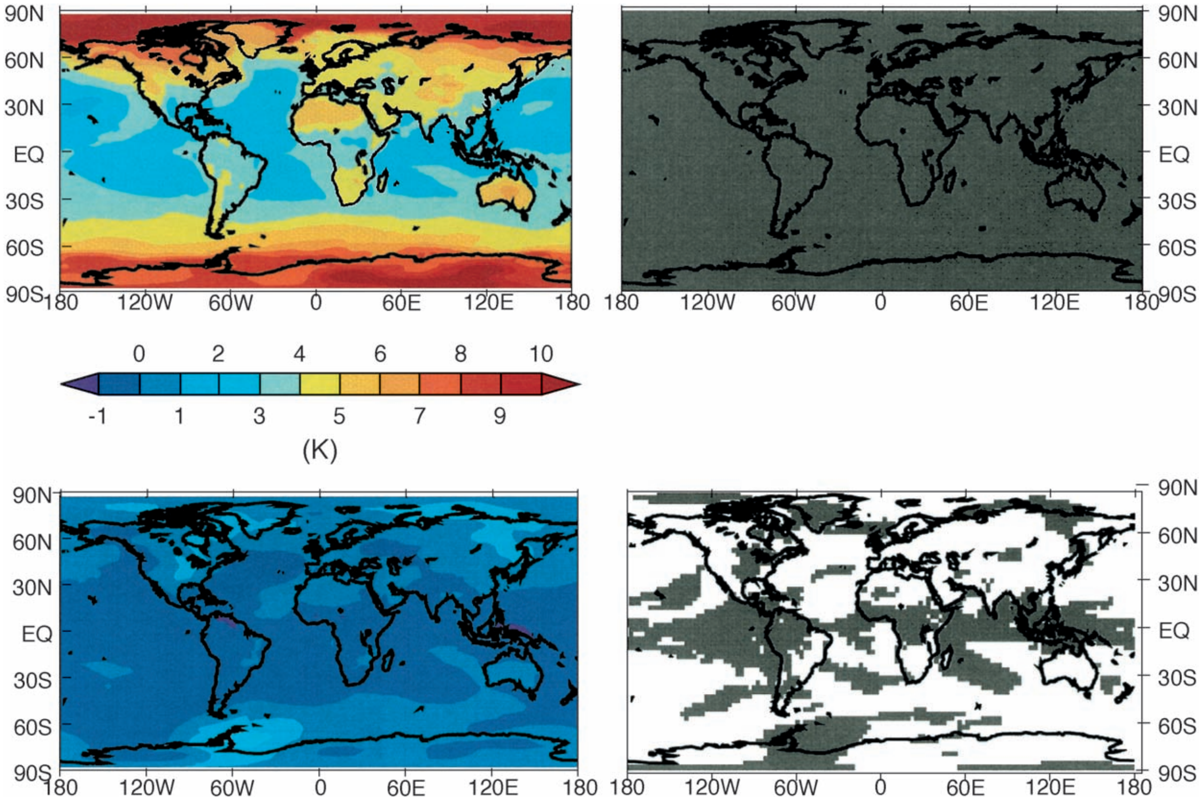

Fig. 2. Surface temperature changes (left panels) and areas with changes that are statistically significant at the 5% level (right panels) for the "$4 \times CO_2$" (top panels) and the "Geoengineered $4 \times CO_2$" (bottom panels) simulations described in the text. Solar radiation has a spatial pattern that differs greatly from that of radiative forcing due to quadrupling atmospheric CO_2 content, yet a reduction in solar forcing largely compensates the temperature response to CO_2 quadrupling.

in CO_2 and changes in solar luminosity. The warming in the "$4 \times CO_2$" climate is statistically significant at the 5% level over 100% of the globe, and is most pronounced in high latitudes where the warming is >8 K. High latitudes warm more than the global mean due to ice albedo feedback. Tropical regions warm less than the global mean due to strong increases in evaporation. In general, because of less evaporation, land areas show more warming than adjacent oceans. In sharp contrast, the "Geoengineered $4 \times CO_2$" simulation shows relatively little surface temperature change. There is a detectable difference (at the 5% significance level) in simulated annual mean temperature between the "Geoengineered $4 \times CO_2$" and Control simulations over 23.9% of Earth's surface; most of these significant differences are in areas with little change but low variability (20°S to 20°N).

The "Geoengineered $4 \times CO_2$" simulation cools most in equatorial regions, because in this region, the reduction in radiative forcing from diminished solar luminosity is greater than the increase in radiative forcing from quadrupled atmospheric CO_2 content. In the tropical latitude band (10°S to 10°N), the annual mean temperature decreases by 0.56 K, with this change significant at 5% level over 76.8% of this area. Therefore, small residual surface temperature change does occur in the tropics in "Geoengineered $4 \times CO_2$" simulation. The small decrease in global and annual mean precipitation and precipitable water (Table 1) are associated with this decrease in surface temperature in low latitudes. Poleward of 60°, the annual mean temperature increases by 0.56 K, with the change significant at 5% level over 23.5% of the area. This increase in surface temperature in high latitudes is consistent with the decrease in sea ice volume in the "Geoengineered 4 × CO_2" simulation compared to the Control (Table 1).

Comparison of surface temperature results by latitude band and season (Table 2) indicates that a reduction in solar luminosity may largely compensate for the impact of increased atmospheric CO_2, despite the differences in the latitudinal and seasonal pattern of these radiative forcings (Fig. 1). Because of ice albedo feedback, the "4 × CO_2" simulation warms more in the winters than summers at high latitudes (Table 2) in both the hemispheres, reducing the amplitude of the seasonal cycle. Geoengineering this "4 × CO_2" world might be expected to diminish this amplitude further, because the reduction in solar luminosity preferentially reduces solar insolation in the high-latitude summers (Fig. 1). However, poleward of 40°N, our "Geoengineered 4 × CO_2" case has average wintertime temperatures reduced by 6.35 K relative to the "4 × CO_2" case, but summertime temperatures reduced by only 3.64 K, despite the fact that a reduction in solar luminosity decreases the insolation in summer more than in the winter. Hence, the amplitude of the seasonal cycle is greater in the geoengineered case than in the "4 × CO_2" case (Table 2). This occurs because there is more sea ice in our geoengineered simulation than in our "4 × CO_2" simulation (Table 1). Sea ice tends to insulate the ocean waters from the colder overlying air, reducing the high-latitude wintertime sensible and latent heat fluxes from the ocean to the atmosphere. In the geoengineered case, relative to "4 × CO_2", the reduction in wintertime ocean-to-atmosphere heat fluxes results in cooling of the winters and amplification of the high-latitude seasonal cycle, bringing it closer to the Control climate. Geoengineered temperatures in these polar regions, for both summer and winter, differ from the Control case by < 0.7 K.

4.3. Stratospheric temperature change

Geoengineering the solar radiation incident on the Earth may largely compensate for CO_2-induced changes on the climate of Earth's surface and troposphere, but it has little impact on stratospheric temperature (Fig. 3). The addition of CO_2 to the atmosphere tends to warm the surface but cool the stratosphere (Manabe and Wetherald, 1975, 1980; Manabe and Stouffer, 1993, 1994; Washington and Meehl, 1989; Murphy and Mitchell, 1995). A reduction in solar luminosity would tend to cool primarily the troposphere; absorption of solar radiation occurs mostly in the troposphere and at surface and less than 1% of the solar radiation is absorbed above the troposphere. Therefore, the stratosphere is little impacted by small reduction in insolation.

In the "4 × CO_2" simulation, the equatorial tropopause warms over 7 K due to large latent heat release in the upper troposphere in the tropics. The other centers of maximum warming are located at the high-latitude surfaces. The stratosphere cools due to enhanced radiation to space and the cooling increases with height, reaching up to ~ 16 K. The Geoengineering simulation largely compensates for the tropospheric warming but cools the stratosphere by an additional ~ 1 K. Zonal mean temperature changes

Table 2
Changes in simulated annual mean surface temperature (K) over different parts of the globe for the "4 × CO_2" and "Geoengineered 4 × CO_2" cases relative to the Control case, for December, January and February (DJF), and June, July and August (JJA)

Latitude Belt	4 × CO_2			Geoengineered 4 × CO_2		
	DJF	JJA	Change in seasonal amplitude	DJF	JJA	Change in seasonal amplitude
Global	+4.11	+3.88	−0.33	−0.06	−0.13	−0.07
N Hemisphere	+4.56	+3.36	−1.20	+0.13	−0.14	−0.27
S Hemisphere	+3.66	+4.40	−0.74	−0.25	−0.11	−0.14
90°N to 40°N	+6.99	+3.87	−3.12	+0.64	+0.23	−0.41
40°N to 10°N	+3.28	+3.11	−0.17	0.00	−0.28	−0.28
10°N to 10°S	+2.83	+3.00	0.17	−0.59	−0.50	0.09
10°S to 40°S	+3.14	+3.39	−0.25	−0.33	−0.16	−0.17
40°S to 90°S	+4.72	+6.30	−1.58	0.05	0.14	−0.09

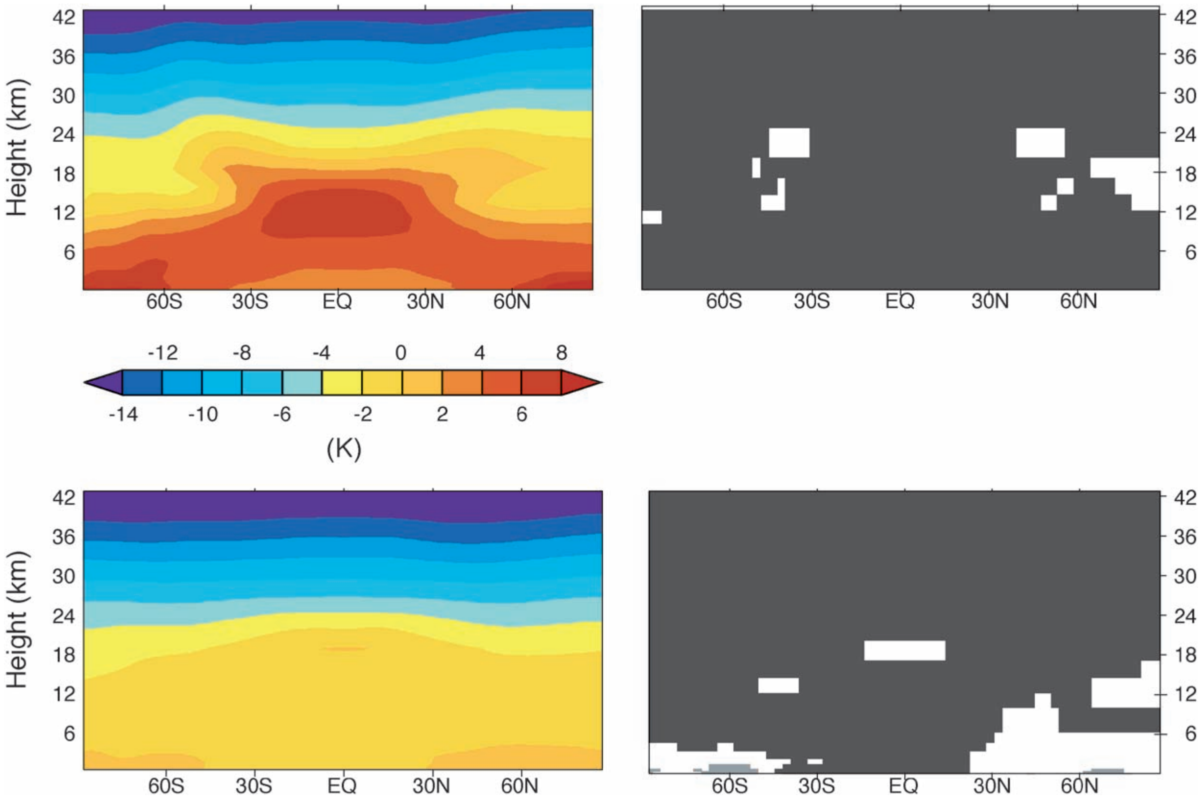

Fig. 3. Zonal mean temperature changes (left panels) and locations with changes that are statistically significant at the 5% level (right panels) for the "$4\times CO_2$" (top panels) and the "Geoengineered $4\times CO_2$" (bottom panels) simulations described in the text. Diminishing the solar radiation incident on the Earth largely compensates the CO_2-induced warming in the troposphere, but cools the stratosphere by an additional ~ 1 K.

(Fig. 3) are generally significant at the 5% level when the change is >0.5 K. Therefore, geoengineering schemes involving placing reflectors outside Earth's atmosphere do not mitigate cooling effect of the greenhouse gases in the stratosphere while counteracting the warming effect in the troposphere. The slightly cooler zonal mean temperatures in the troposphere are consistent with the decreased precipitable water in "Geoengineered $4\times CO_2$" simulation compared to Control (Table 1). The additional cooling of the stratosphere in the "Geoengineered $4\times CO_2$" case could aggravate the enhancement of the formation of polar stratospheric clouds, which could in turn increase the destruction of stratospheric Ozone (Houghton et al., 1990). The reduction of Ozone could in turn decrease the temperature further. Geoengineering approaches involving placing aerosols in the stratosphere (Flannery et al., 1997; Teller et al., 1997) could have additional adverse impacts on stratospheric chemistry (Kinnison et al., 1994). We do not model stratospheric chemistry in this study, and hence, detailed stratospheric chemistry models will be required to address the precise impacts in the stratosphere.

4.4. Hydrological cycle

In general, the model's hydrological cycle (e.g. precipitation) does not show a strong sensitivity to a quadrupling of CO_2 (Table 1). Some models (for example, the GFDL model) show much stronger sensitivity in hydrological cycle (Manabe and Wetherald, 1980). Therefore, our results may not be reflective of results from other models. Changes in the annual mean net freshwater flux (precipitation minus evaporation) were statistically significant at the 5% level over only 55.4% and 8.5% of Earth's surface, for the "$4 \times CO_2$" and "Geoengineered $4 \times CO_2$" simulations, respectively. Changes in annual mean precipitation (P), evaporation (E) and net water flux ($P - E$) are given in Table 3. For the "$4 \times CO_2$" case, we find uniform increases in evaporation, whereas Manabe and Stouffer (1994) find the enhancement in evaporation decreases from low latitudes to high latitudes. As found in other studies (Murphy and Mitchell, 1995; Manabe and Stouffer, 1993, 1994), we find a significant increase in precipitation and net freshwater flux into the surface in the high latitudes (poleward of 40°) in the "$4 \times CO_2$" simulation. The net flux into the surface increases in the tropics (10°S to 10°N) and decreases in subtropics (10–40°) in both hemispheres in our "$4 \times CO_2$" simulation. In contrast, Manabe and Stouffer (1994) find a decrease in net water flux in the tropics for their $4 \times CO_2$ case in their coupled model study. We did not find any statistically significant changes in the simulated annual mean volumetric soil water content.

In the tropics, net water flux into the surface increases by 0.23 mm day^{-1} in the "$4 \times CO_2$" simulation and decreases by 0.136 in the "Geoengineered $4 \times CO_2$" simulation, with the change significant at the 5% level over 17.9% of Earth's area in both the simulations. In the "Geoengineered $4 \times CO_2$" simulation, the decrease in net water flux occurs in the tropics because the reduction in solar forcing is strongly experienced there in the annual mean. The decrease in surface temperature in the tropics (Fig. 2) is consistent with the reduction in precipitation and evaporation there in the "Geoengineered $4 \times CO_2$" simulation.

Poleward of 40°, the net freshwater flux in our "$4 \times CO_2$" simulation increases by 0.113 mm day^{-1}, with the change in this flux significant at the 5% level over 51% of this area. However, in the "Geoengineered $4 \times CO_2$" simulation, the change in high-latitude freshwater flux is only 0.043 mm day^{-1}, and is statistically significant over only 5.8% of this area. The net water flux changes are significant at 5% level in the subtropics over 35.9% and 6.8% of the area in the "$4 \times CO_2$" and "Geoengineered $4 \times CO_2$" simulations, respectively. To summarize, the changes in net water fluxes are not significant in the geoengineered simulation except in tropics where there is a reduction in net water flux.

It has been suggested that a shutdown of North Atlantic thermohaline circulation could be a consequence of CO_2-induced increases in surface temperature and net freshwater flux in the high latitudes (Manabe and Stouffer, 1993, 1994; Rahmstorf, 1996, 2000). Our results suggest that geoengineering the solar radiation incident on the Earth might diminish the impact of increased CO_2 on both of these quantities, making a shutdown of the ocean's thermohaline circulation less likely. Further, the melting of Greenland and Antarctic ice caps and the consequent sea level rise is less likely to occur in a geoengineered world. However, the simulated reduction in precipitation in the tropics in our geoengineered simulation

Table 3
Changes in annual mean precipitation, evaporation and net freshwater flux over different parts of the globe for the "$4 \times CO_2$" and "Geoengineered $4 \times CO_2$" cases relative to the Control case

Case	Precipitation (mm/day)		Evaporation (mm/day)		Net water flux (mm/day)	
	$4 \times CO_2$	Geoengineered $4 \times CO_2$	$4 \times CO_2$	Geoengineered $4 \times CO_2$	$4 \times CO_2$	Geoengineered $4 \times CO_2$
Global	0.226	−0.096	0.226	−0.096	0	0
Land	0.216	−0.088	0.136	−0.044	0.080	−0.044
Ocean	0.230	−0.100	0.263	−0.119	−0.033	0.019
N Hemisphere	0.154	−0.043	0.240	−0.086	−0.086	0.043
S Hemisphere	0.298	−0.149	0.212	−0.106	0.086	−0.043
90°N to 40°N	0.331	−0.052	0.220	−0.008	0.111	−0.044
40°N to 10°N	−0.040	0.007	0.256	−0.105	−0.296	0.122
10°N to 10°S	0.449	−0.342	0.219	−0.206	0.230	−0.136
10°S to 40°S	0.122	−0.055	0.222	−0.137	−0.100	0.082
40°S to 90°S	0.325	−0.055	0.210	−0.014	0.115	−0.041

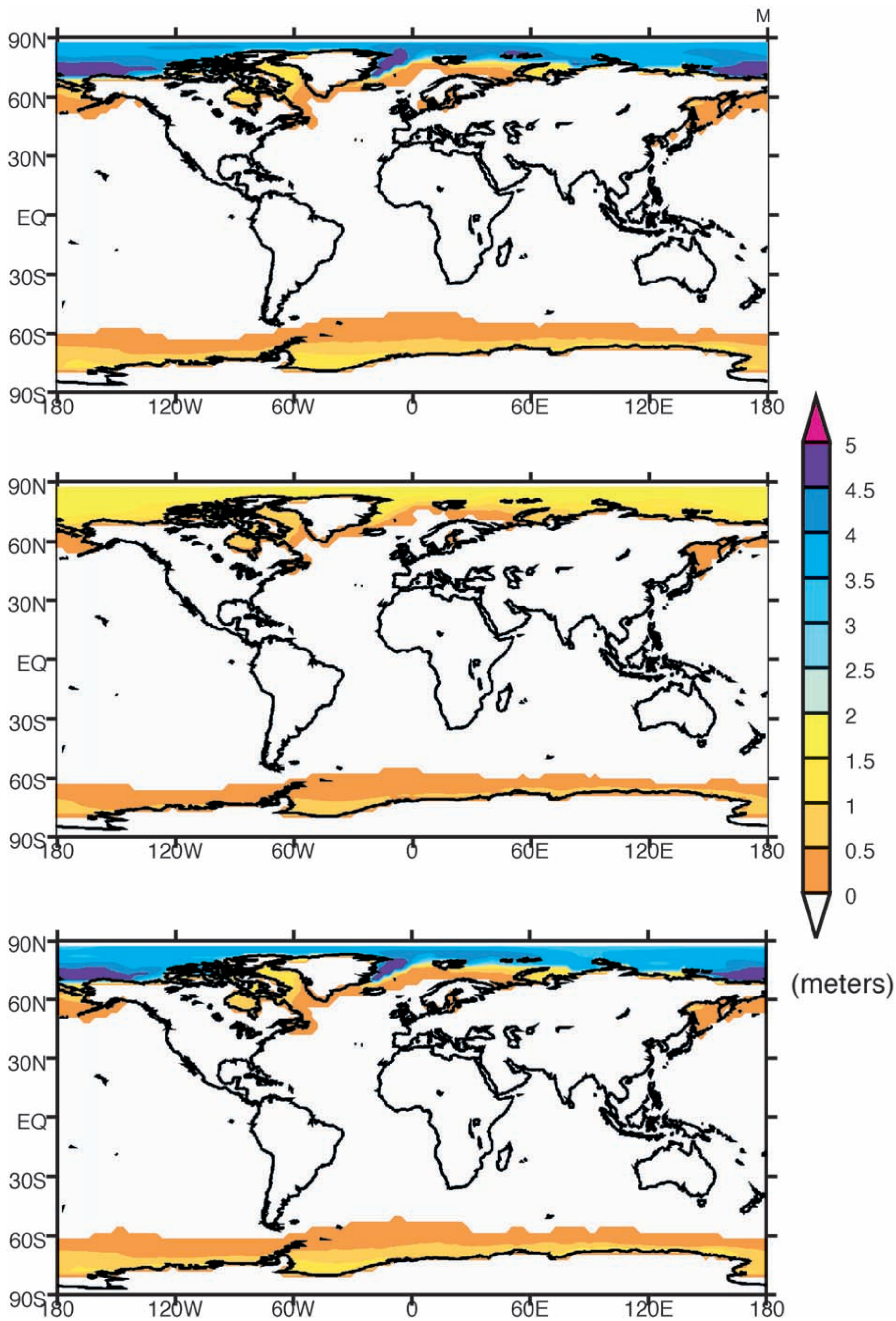

Fig. 4. Annual mean sea ice thickness in the Control (top panel), "$4 \times CO_2$" (middle panel) and "Geoengineered $4 \times CO_2$" (bottom panel) simulations. The reduction in solar forcing in "Geoengineered $4 \times CO_2$" simulation largely compensates the decrease in sea ice thickness and area coverage in the "$4 \times CO_2$" simulation.

could have consequences for agriculture in that region. The economic and environmental implications of this change must be addressed.

4.5. Sea ice

Fig. 4 shows the annual mean sea ice thickness and its area coverage in the three experiments. In the preindustrial control simulation, the simulated maximum annual mean thickness of sea ice is about 5 m in Arctic and 1.44 m in Antarctic. In the model, as in real world, the sea ice in the Southern Hemisphere is seasonal; it almost vanishes in Southern Hemisphere summer. However, sea ice in the Arctic is permanent. In the "$4 \times CO_2$" simulation, annual mean sea ice thickness decreases drastically at all sea ice points. The maximum thickness decreases to 1.9 m in Arctic and 1 m in Antarctic. The sea ice area coverage also shrinks, most notably in the Southern Hemisphere. In the "Geoengineered $4 \times CO_2$" simulation, sea ice thickness and area coverage are almost recovered to the levels in the control simulation, though the annual and global mean sea ice volume is slightly lower than in the control simulation (Table 1).

It should be noted that the sea ice in our model does have seasonal variations. However, our simulation of Arctic and Antarctic processes has uncertainties due to the following limitations: (1) sea ice dynamics is neglected; (2) the effect of fresh water flux and salinity on sea ice are not considered; (3) the heat transport by the ocean is prescribed; (4) the prescribed depth of the mixed layer does not have seasonal variations.

5. Discussion and conclusion

An analysis of several paleoclimates and paleoradiative forcing reconstructions indicated that the latitudinal structure of temperature response to climate forcing is insensitive to the details of the latitudinal structure of the radiative forcing (Hoffert and Covey, 1992). In a set of atmospheric GCM simulations with specified ocean heat transport (Covey and Thompson, 1989), total poleward heat transport was largely insensitive to the specified ocean heat transport, as changes in atmospheric heat transport largely compensated for changes in ocean heat transport. Our results and these findings suggest that the response of the climate system to external forcing is somewhat insensitive to the detailed spatial and/or temporal distribution of that forcing. A more realistic treatment of the oceans could modify this a bit. The relative independence of the geographic and seasonal climate response may complicate the attribution of climate changes to specific forcings. Of course, this relative independence of climate response from the details of the climate forcing has limits. For example, the climate response "fingerprint" of sulfate aerosols is quite distinguishable from that of carbon dioxide (Taylor and Penner, 1994).

Our results suggests that geoengineering may be a promising strategy for counteracting climate change, as it may not be necessary to replicate the exact radiative forcing patterns from greenhouse gases to largely negate their effects. However, subtle changes in the distribution of solar luminosity associated with the Milankovitch cycles (Imbrie et al., 1984) may have produced large climate change on time scales $>10^4$ years, after ocean circulation and ice sheets adjusted to the slightly modified new climate. Hence, even if geoengineering schemes could largely compensate for the climate change induced by a CO_2 doubling or quadrupling on short time scales, there is no guarantee that long-term climate would remain relatively unaffected. For instance, the uptake of CO_2 by the biosphere will increase at elevated levels of atmospheric CO_2, irrespective of whether we implement geoengineering schemes or not.

We have performed equilibrium climate simulations using a single atmospheric general circulation model coupled to a slab ocean and thermodynamic sea ice model. It is possible that other atmospheric GCMs would yield quantitatively different results (Hansen et al., 1999). Climate models exhibit a wide range of response for similar climate forcings (Hansen et al., 1997). Results may be highly sensitive to the formulation of the model and the parameterization of various physical processes (Hansen et al., 1999). For instance, in the GFDL coupled model simulations (Manabe and Stouffer, 1994), the global mean surface air temperature increases by 3.5 and 7 K in the doubling and quadrupling experiments, respectively. The GFDL model has a higher climate sensitivity and apparently constant climate sensitivity for increases in CO_2. In contrast, CCM3 has a much lower sensitivity (1.75 and

4.02 K for doubling and quadrupling) that increases for increasing concentrations of CO_2 (Kothavala et al., 1999).

Our study considers anthropogenic forcing only from carbon dioxide. Results may differ for other radiatively active gases or aerosols. Simulations using a coupled atmosphere, dynamic sea ice and ocean general circulation models would include dynamical feedbacks involving the thermohaline circulation that could amplify the regional or global climate change simulated for geoengineering scenario (Manabe and Stouffer, 1993, 1994). Furthermore, we have considered only a steady state, and the transient responses of the climate system need to be addressed.

Geoengineering schemes impose a variety of technical, environmental and economic challenges (Early, 1989; Seifritz, 1989; National Academy of Sciences, 1992; Watson et al., 1995; Flannery et al., 1997; Teller et al., 1997). For instance, in the case of placing reflectors in space, since a quadrupling of CO_2 requires the interception of about 3.6% of the sunlight incident on the Earth, an interception area of $\sim 4.6 \times 10^6$ km^2 or a disk of roughly 1200 km in radius has to be built. To counteract a transient warming, the solar input has to diminish over time as CO_2 increases. If CO_2 increases at the current rate of $\sim 0.4\%$ year^{-1} (Houghton et al., 1995), to counteract this warming, we would need to build $\sim 1.2 \times 10^4$ km^2 of interception area each year. Other options also involve great difficulties. Placing small particles or aerosols in the stratosphere may not result in uniform diminution of radiation. Mirrors in low Earth orbit will lead to flickering of the Sun $\sim$ 4% of the time, and involves tracking problems so that mirrors do not collide with each other. Reflectors or scatterers at the Lagrange point between the Sun and Earth involve large costs. Ecosystems would be impacted by changes in atmospheric CO_2 content and photosynthetically active radiation, even without climate change.

The failure of a geoengineering system could subject the Earth to extremely rapid warming. Ethical and political concerns differ depending on whether global-scale climate modification is intentional (e.g. geoengineering) or merely a predictable consequence (e.g. fossil fuel burning) of our actions. Many of the geoengineering schemes are cooperative solutions that require continuous world management for multiple centuries. Given the history of noncooperation at a global scale just in the 20th century, there is very high probability of the nonfeasibility of geoengineering of cooperative solutions (Schneider, 2001).

Given these difficulties, the most prudent and least risky option to mitigate global warming may well be to curtail emissions of greenhouse gases (Hoffert et al., 1998). Nevertheless, it is useful to study geoengineering schemes that may provide options in the event that greenhouse gas emissions induce a truly catastrophic climate response.

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References

Budyko, M.I., 1977. Climate Changes. American Geophysical Union, Washington, DC. 244 pp. (English translation of 1974 Russian volume).

Chervin, R.M., Schneider, S.H., 1976a. A study of the response of NCAR GCM climatological statistics to random perturbations: estimating noise levels. J. Atmos. Sci. 33, 392–404.

Chervin, R.M., Schneider, S.H., 1976b. On determining the statistical significance of climate experiments with general circulation models. J. Atmos. Sci. 33, 405–412.

Covey, C., Thompson, S.T., 1989. Testing the effects of ocean heat transport on climate. Palaeogeogr. Palaeoclimat. Palaeoecol. (Glob. Planet. Change Sec.) 75, 331–441.

Early, J.T., 1989. The space based solar shield to offset greenhouse effect. J. Br. Interplanet. Soc. 42, 567–569.

Flannery, B.P., Kheshgi, H., Marland, G., MacCracken, M.C., 1997. Geoengineering climate. In: Watts, R. (Ed.), Engineering Response to Global Climate Change. Lewis Publishers, Boca Raton, FL, pp. 403–421.

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

Hansen, J.E., Sato, M., Ruedy, R., 1997. Radiative forcing and climate response. J. Geophys. Res. 102, 6831–6863.

Hansen, J.E., Sato, M., Lacis, A., Reudy, R., Tegen, I., Mathews, E., 1999. Climate forcings in the industrial era. Proc. Natl. Acad. Sci. 95, 12753–12758.

Hoffert, M.I., Covey, C., 1992. Deriving global climate sensitivity from palaeoclimate reconstructions. Nature 360, 573–576.

Hoffert, M.I., Caldeira, K., Jain, A.K., Haites, E.F., et al., 1998. Energy implications of future stabilization of atmospheric CO_2 content. Nature 395, 881–884.

Houghton, J.T., Jenkins, G.J., Ephraums, J.J., 1990. Climate Change: the IPCC Scientific Assessment. Intergovernmental Panel on Climate Change, United Nations Environmental Program/World Meteorological Organization, Cambridge Univ. Press, New York, 365 pp.

Houghton, J.T., Filho, L.G.M., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K., 1995. Climate Change 1995: the Science of Climate Change. Intergovernmental Panel on Climate Change, United Nations Environmental Program/World Meteorological Organization. Cambridge Univ. Press, New York, 572 pp.

Imbrie, J., et al., 1984. The orbital theory of Pleistocene climate: support from a revised chronology of $\delta^{18}O$ record. In: Berger, A., et al., (Eds.), Milankovitch and Climate. D. Reidel, Dordrecht, Netherlands, pp. 269–305.

Kiehl, J.T., Briegleb, B.P., 1993. The relative roles of sulfate aerosols and greenhouse gases in climate forcing. Science 260, 311.

Kiehl, J.T., Hack, J.J., Bonan, G.B., Boville, B.A., Briegleb, B.P., Williamson, D.L., Rasch, P.J., 1996. Description of the NCAR Community Climate Model (CCM3). NCAR technical note, NCAR/TN-420 + STR, 152 pp.

Kinnison, D.E., Grant, K.K., Connell, P.S., Rotman, D.A., Wuebbles, D.J., 1994. The chemical and radiative effects of the Mount Pinatubo eruption. J. Geophys. Res.—Atmos. 99, 25705–25731.

Kothavala, Z., Oglesby, R.J., Saltzman, B., 1999. Sensitivity of equilibrium surface temperature of CCM3 to systematic changes in atmospheric CO_2. Geophys. Res. Lett. 26, 209–212.

List, R.J. (Ed.), 1951. Meteorological Table, 6th ed. Smithsonian Institute, Washington, DC, 527 pp.

Manabe, S., Stouffer, R.J., 1993. Century-scale effects of increased atmospheric CO_2 on the ocean atmosphere system. Nature 364, 215–218.

Manabe, S., Stouffer, R.J., 1994. Multiple-century response of a coupled ocean–atmosphere model to an increase of atmospheric carbon dioxide. J. Climate 7, 5–23.

Manabe, S., Wetherald, R.T., 1975. The effects of doubling the CO_2 concentration on the climate of a general circulation model. J. Atmos. Sci. 32, 3–15.

Manabe, S., Wetherald, R.T., 1980. On the distribution of climate change resulting from an increase in CO_2 content of the atmosphere. J. Atmos. Sci. 37, 99–118.

Murphy, J.M., Mitchell, J.F.B., 1995. Transient response of the Hadley Center coupled ocean–atmosphere model to increasing carbon dioxide. J. Climate 8, 57–80.

National Academy of Sciences, 1992. Policy Implications of Greenhouse Warming: Mitigation, Adaptation and the Science Base. National Academy Press, Washington, DC, pp. 433–464. Chap. 28, Geoengineering.

Press, W.H., Flannery, B.P., Teukolsky, S.A., 1989. Numerical Recipes. Cambridge Univ. Press, New York, 702 pp.

Rahmstorf, S., 1996. On the freshwater forcing and transport of the Atlantic thermohaline circulation. Clim. Dyn. 12, 799–811.

Rahmstorf, S., 2000. The thermohaline ocean circulation: a system with dangerous thresholds? An editorial comment. Clim. Change 46, 247–256.

Schneider, S.H., 1996. Geoengineering—could or should we do it. Clim. Change 33, 291–302.

Schneider, S.H., 2001. Earth systems engineering and management. Nature 409, 417–421.

Seifritz, W., 1989. Mirrors to halt global warming? Nature 340, 603.

Taylor, K.E., Penner, J.E., 1994. Response of the climate system to atmospheric aerosols and greenhouse gases. Nature 369, 734–737.

Teller, E., Wood, L., Hyde, R., 1997. Global Warming and Ice Ages: I. Prospects for Physics Based Modulation of Global Change. UCRL-231636/UCRL JC 128715. Lawrence Livermore National Laboratory, Livermore, CA, USA.

Washington, W.M., Meehl, G.A., 1989. Climate sensitivity due to increased CO_2: experiments with a coupled model and ocean general circulation model. Clim. Dyn. 4, 1–38.

Watson, R.T., Zinyowera, M.C., Moses, R.H., Dokken, D.J., 1995. Climate change 1995: impacts, adaptations and mitigation of climate change: scientific–technical analyses. Intergovernmental Panel on Climate Change, United Nations Environmental Program/World Meteorological Organization. Cambridge Univ. Press, pp. 799–822. Chap. 25.

Zwiers, F.W., Storch, H.V., 1995. Taking serial correlation into account in tests of the mean. J. Climate 8, 336–351.