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Geoengineering Earth's radiation balance to mitigate CO_2-induced climate change

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Abstract. To counteract anthropogenic climate change, several schemes have been proposed to diminish solar radiation incident on Earth's surface. These geoengineering schemes could reverse global annual mean warming; however, it is unclear to what extent they would mitigate regional and seasonal climate change, because radiative forcing from greenhouse gases such as CO_2 differs from that of sunlight. No previous study has directly addressed this issue. In the NCAR CCM3 atmospheric general circulation model, we reduced the solar luminosity to balance the increased radiative forcing from doubling atmospheric CO_2. Our results indicate that geoengineering schemes could markedly diminish regional and seasonal climate change from increased atmospheric CO_2, despite differences in radiative forcing patterns. Nevertheless, geoengineering schemes could prove environmentally risky.

Introduction

Several schemes have been proposed to counteract the warming influence of increasing atmospheric CO_2 content via intentional manipulation of Earth's radiation balance [*Budyko,* 1977; *Early,* 1989; *NAS,* 1992; *Watson et al.,* 1995; *Flannery et al.,* 1997; *Teller et al.,* 1997]. Proposed "geoengineering" schemes typically involve placing reflectors or scatterers in the stratosphere or in orbit between the Earth and Sun, diminishing the amount of solar radiation incident on the Earth. However, the radiative forcing from increased atmospheric carbon dioxide [*Kiehl and Briegleb,* 1993] differs markedly (Plate 1) from that of a change in effective solar luminosity [*List,* 1951]. Carbon dioxide traps heat in both day and night over the entire globe, whereas diminished 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. One might expect [*Schneider,* 1996], therefore, 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 in an undisturbed climate.

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The Model and Experiments

We investigated these issues using the standard configuration of the Community Climate Model (CCM3), with a simple slab ocean and thermodynamic sea-ice model, developed at the National Center for Atmospheric Research [*Kiehl et al.,* 1996]. We performed three model simulations: (i) "Control" or pre-industrial, with a CO_2 content of 280 ppm and a solar "constant" of 1367 W m^{-2}; (ii) "Doubled CO_2", with doubled atmospheric CO_2 content (560 ppm), but the same solar constant as the Control simulation; and (iii) "Geoengineered", with doubled atmospheric CO_2 content and the solar constant reduced by 1.8% to approximately offset the radiative forcing from a CO_2 doubling (4.17 W m^{-2}). This reduction in incident solar radiation could be effected through the placement of reflecting or scattering devices between the Earth and Sun [*Early,* 1989; *Flannery et al.,* 1997; *Teller et al.,* 1997]. The resulting net change in radiative forcing generally would be an order of magnitude smaller than that associated with Milankovitch cycles [*Imbrie et al.,* 1984].

For the experiments presented here, the model was run for 40 years; climate statistics were calculated for the last 15 years. We assessed the statistical significance of the difference in the means between the test (Doubled-CO_2 or Geoengineered) and Control simulations at each model-grid point using the Student-t test [*Press et al.,* 1989], corrected for the influence of serial correlation [*Zwiers and Storch,* 1995].

Results

In the Doubled-CO_2 simulation, the planet warms 1.75 K, leading to reduced sea-ice volume and increased precipitation (Table 1). The 1.8% reduction in solar luminosity cools the Earth 1.88 K from its doubled-CO_2 state. We estimate that a shielding of ~1.7% of incident solar radiation would more exactly compensate the effect of a CO_2 doubling in this model.

The warming in the Doubled-CO_2 climate (Plate 2) is statistically significant at the 5% level over 97.4% of the globe, and is most pronounced in high latitudes. In sharp contrast, the Geoengineered simulation shows relatively little surface temperature change. There are significant differences (at the 5% level) in annual mean temperature between the Geoengineered and Control

Table 1. Global annual mean model results.

Case	Surface temperature (K)	Precipitation (mm/day)	Sea ice volume (10^{12} m^3)
Control	285.50	2.98	51.2
Doubled CO_2	287.25	3.07	38.7
Geoengineered	285.37	2.92	51.5

simulations over only 15.1% of Earth's surface, primarily in areas with little change but low variability.

The Geoengineered simulation cools most in equatorial regions (Table 2), because in this region the reduction in radiative forcing from diminished solar flux is greater than the increase in radiative forcing from doubled atmospheric CO_2. Diminished daytime solar heating in the Geoengineered simulation relative to the Control reduces the amplitude of the diurnal cycle over land by only ~0.1 K.

At high latitudes, the Doubled-CO_2 simulation warms more in winter than summer, reducing the amplitude of the seasonal cycle (Table 2). Geoengineering this doubled-CO_2 world might be expected to diminish this amplitude further, because solar insolation would be preferentially reduced in high latitude summers (Plate 1). However, the amplitude of the seasonal cycle is greater in the Geoengineered case than in the Doubled-CO_2 case. This occurs because there is more sea ice in our Geoengineered simulation than in our Doubled-CO_2 simulation (Table 1). Sea ice tends to insulate the ocean waters from the colder overlying air, reducing the high-latitude wintertime heat flux from the ocean to the atmosphere. In the Geoengineered case, relative to Doubled-CO_2, the reduction in wintertime ocean-to-atmosphere heat flux results in colder winters and amplification of the high-latitude seasonal cycle, bringing it closer to the Control climate.

Proposed geoengineering schemes would exacerbate the impact of CO_2 on stratospheric temperature (Plate 3). Increasing atmospheric CO_2 tends to warm the surface but cool the stratosphere [*Murphy and Mitchell,* 1995], whereas diminished solar radiation tends to cool the atmosphere everywhere. Enhanced stratospheric cooling could contribute to the destruction of stratospheric ozone [*Houghton et al.,* 1990]. 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].

In general, the model's hydrological cycle (e.g., precipitation) does not show a strong sensitivity to doubling CO_2 (Table 1). Changes in the annual mean net fresh water flux (precipitation minus evaporation) were statistically significant at the 5% level over only 13.9% and 3.9% of Earth's surface, for the Doubled-CO_2 and Geoengineered simulations, respectively. Other quantities, including zonal winds and specific humidity, also showed little significant change between the Geoengineered and Control simulations.

As found in other studies [*Murphy and Mitchell,* 1995; *Manabe and Stouffer,* 1993], there is an increased net fresh water flux to the surface at high latitudes in the Doubled-CO_2 simulation. Poleward of 60° the net fresh water flux in our Doubled-CO_2 simulation increases by 0.130 mm day^{-1}, with the change in this flux significant at the 5% level over 51.7% of this area. However, in the Geoengineered simulation, this increase in high-latitude fresh-water flux is only 0.008 mm day^{-1}, and is significant over only 1.8% of this area. It has been suggested that a shutdown of North Atlantic thermohaline circulation could be a consequence of CO_2-induced increases

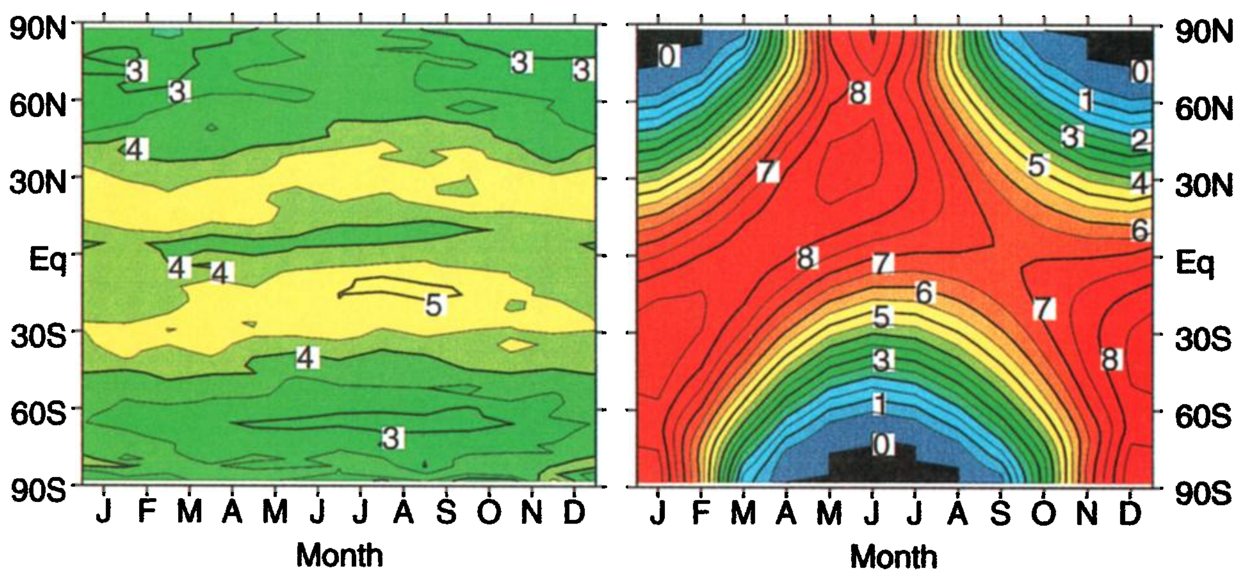

Plate 1. Change in net longwave radiative flux at the tropopause when CO_2 is doubled (left panel) with respect to the control case and the reduction in incoming solar radiation (right panel) needed to compensate this forcing. Both values (W m^{-2}) are zonally averaged as a function of time of year.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

Table 2. Changes in simulated mean surface temperature (K) in three latitude bands for the Doubled-CO_2 and Geoengineered cases relative to the Control case, for December, January, and February (DJF), and June, July and August (JJA).

Latitude Belt	Doubled CO_2			Geoengineered		
	DJF	JJA	Change in amplitude of seasonal cycle	DJF	JJA	Change in amplitude of seasonal cycle
90 N to 20 N	+2.33	+1.67	−0.66	+0.15	−0.06	−0.21
20 N to 20 S	+1.31	+1.36		−0.31	−0.27	
20 S to 90 S	+1.70	+2.01	−0.31	−0.15	−0.08	−0.07

in surface temperature and net-fresh-water flux in the high latitudes [*Manabe and Stouffer*, 1993]. Our results indicate 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, melting of Greenland and Antarctic ice caps and the consequent sea level rise is less likely to occur in a geoengineered world.

Discussion and Conclusion

Our results suggest 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, 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 that could amplify the regional or seasonal climate impacts [*Manabe and Stouffer,* 1993]. Furthermore, we have considered only a steady-state doubled-CO_2 scenario and not the transient responses of the climate system.

Geoengineering schemes impose a variety of technical, environmental, political, and economic challenges [*Early,* 1989; *NAS,* 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 doubling of CO_2 requires the interception of about 1.7% of the sunlight incident on the Earth, an interception area of ~2 x 10^6 km^2 or a disk of roughly 800 km in radius. To counteract CO_2 increasing at the rate of ~0.4% yr^{-1} [*Houghton et al.,* 1995], we would need to build ~1.2 x 10^4 km^2 of interception area each year. Other options also involve great difficulties. Placing small particles

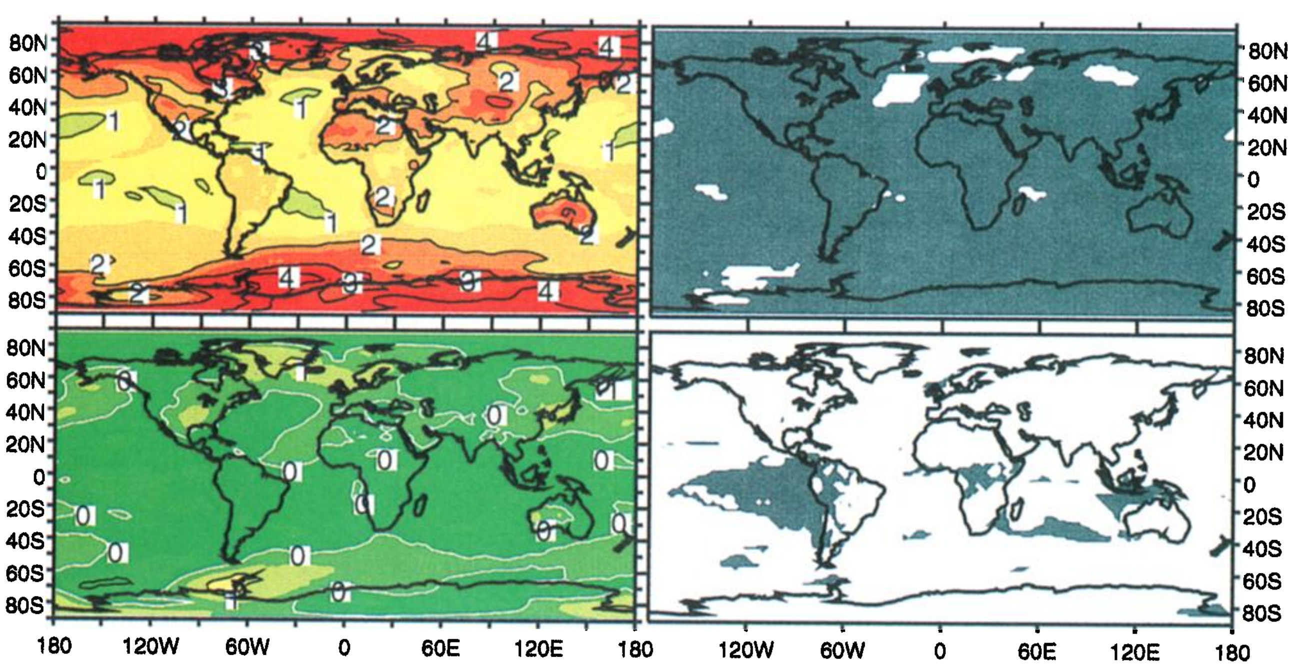

Plate 2. Surface temperature changes (left panels) and areas with changes that are statistically significant at the 5% level (right panels) for the Doubled-CO_2 (top panels) and the Geoengineered (bottom panels) simulations. Solar radiation has a spatial pattern that differs greatly from that of radiative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

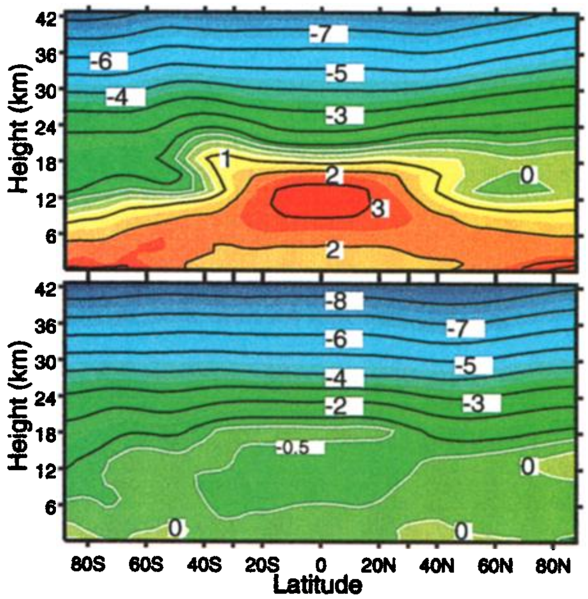

Plate 3. Zonal mean temperature changes for the Doubled-CO_2 (top panel) and Geoengineered (bottom panel) simulations as a function of latitude and height above Earth's surface. Diminishing the solar radiation incident on the Earth largely compensates the CO_2-induced warming in the troposphere, but cools the stratosphere by an additional 0.9 K. Zonal mean temperature changes are generally significant at the 5% level when the change is > 0.5 K.

or aerosols in the stratosphere may not result in uniform diminution of radiation. Mirrors in low-earth orbit would lead to flickering of the sun ~2% of the time, and involve tracking problems to avoid collision. Reflectors or scatterers at the Lagrange point between the Sun and Earth involve large costs. 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 or merely a predictable consequence of our actions. Ecosystems would be impacted by changes in atmospheric CO_2 content and available sunlight. 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].

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