Transient climate–carbon simulations of planetary geoengineering

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Geoengineering (the intentional modification of Earth's climate) has been proposed as a means of reducing CO_2-induced climate warming while greenhouse gas emissions continue. Most proposals involve managing incoming solar radiation such that future greenhouse gas forcing is counteracted by reduced solar forcing. In this study, we assess the transient climate response to geoengineering under a business-as-usual CO_2 emissions scenario by using an intermediate-complexity global climate model that includes an interactive carbon cycle. We find that the climate system responds quickly to artificially reduced insolation; hence, there may be little cost to delaying the deployment of geoengineering strategies until such a time as "dangerous" climate change is imminent. Spatial temperature patterns in the geoengineered simulation are comparable with preindustrial temperatures, although this is not true for precipitation. Carbon sinks in the model increase in response to geoengineering. Because geoengineering acts to mask climate warming, there is a direct CO_2-driven increase in carbon uptake without an offsetting temperature-driven suppression of carbon sinks. However, this strengthening of carbon sinks, combined with the potential for rapid climate adjustment to changes in solar forcing, leads to serious consequences should geoengineering fail or be stopped abruptly. Such a scenario could lead to very rapid climate change, with warming rates up to 20 times greater than present-day rates. This warming rebound would be larger and more sustained should climate sensitivity prove to be higher than expected. Thus, employing geoengineering schemes with continued carbon emissions could lead to severe risks for the global climate system.

carbon cycle | climate change | geoengineering | climate forcing | managing solar radiation

Climate change is one of the most serious environmental challenges facing human and environmental systems. Impacts of climate change from accumulating greenhouse gases are slow to manifest, and individual climate events are difficult to link directly to human activities. However, accelerating greenhouse gas emissions have pushed and will continue to push the climate system toward increasing global temperatures. Although it is not certain what or how serious the impacts of climate change will be over the next century, there will be increasing impacts on human societies and the environment.

It is also clear that efforts to mitigate the growth rate of human greenhouse gas emissions through international cooperation have fallen short of even the modest targets that have been set. The slow progress of mitigation efforts combined with recent evidence of increasing climate impacts (e.g., large arctic warming and an accelerated melting of Greenland ice sheets) have prompted some climate scientists to suggest that we may be closer to "dangerous" levels of anthropogenic climate change than had previously been thought (1). It is perhaps not surprising that there has been recent renewed interest in possible top-down technological fixes of the climate/energy problem designed to restrict climate warming by intentionally counteracting the radiative effects of anthropogenic greenhouse gases (2, 3).

Geoengineering (the intentional modification and/or management of the earth's climate system) is not a new idea. In 1992, the U.S. National Academy of Sciences published a report on the policy implications of global warming in which a full chapter was devoted to the technical feasibility and possible implications of various geoengineering proposals (4). In recent literature, the term "geoengineering" has most often been used to refer to techniques to reduce absorption of incoming solar radiation, via schemes such as the injection of reflective aerosols into the stratosphere (e.g., refs. 2 and 3). Other proposals to manage incoming solar radiation have included the manufacture and deployment of space-based solar reflectors and large-scale cloud seeding to increase the distribution of marine stratocumulus clouds (4). Geoengineering has also been used to describe the management of carbon sinks, for example, through large-scale reforestation, ocean fertilization, or carbon capture with direct ocean injection (5, 6). However, we emphasize that there is an important difference between managing solar radiation and managing carbon sinks; for the purposes of this paper, we restrict our definition of geoengineering to refer to planetary-scale efforts to reduce the absorption of incoming sunlight.

Many questions arise when considering the technical feasibility and cost of such proposals (4). Even less is known, however, about the climate implications of geoengineering. Proposed schemes to reduce incoming solar radiation (e.g., ref. 3) have drawn on the climatic effect of large volcanic eruptions (e.g., Mt. Pinatubo in 1991), which inject sulfate aerosols into the stratosphere and generate global cooling of a few tenths of a degree for several years after an eruption (7). By extension, it is possible that deliberate (and repeated) injection of aerosols into the stratosphere would affect a long-term cooling that could compensate for some (or perhaps all) of the climate warming induced by anthropogenic greenhouse gases.

To date, only a handful of model simulations have addressed the climatic consequences of such geoengineering proposals. The first such study (8) showed that a globally uniform reduction of absorbed solar radiation could in fact compensate for the spatial heterogeneity of greenhouse and other anthropogenic climate forcings. In a subsequent study, the authors showed that the global biospheric effects of reduced insolation may be small in comparison to the possible fertilization of terrestrial ecosystems from elevated atmospheric CO_2 (9). However, these studies were carried out in the context of idealized doubled CO_2 experiments, which did not capture the time-dependent implications for the climate system of a world subject to both continued CO_2 emissions and large-scale geoengineering.

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Abbreviation: UVic ESCM, University of Victoria Earth System Climate Model.

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Table 1. Description of model runs

Model run	Description
A2	Observed CO_2 concentrations followed by Special Report on Emissions Scenarios A2 CO_2 emissions
GEO	A2 with geoengineering implemented at 2000
ON_2025	A2 with geoengineering implemented at 2025
ON_2050	A2 with geoengineering implemented at 2050
ON_2075	A2 with geoengineering implemented at 2075
OFF_2025	GEO with geoengineering failure at 2025
OFF_2050	GEO with geoengineering failure at 2050
OFF_2075	GEO with geoengineering failure at 2075
A2+CS	A2 with doubled climate sensitivity after 2005
GEO+CS	GEO with doubled climate sensitivity after 2005
OFF_2050+CS	OFF_2050 with doubled climate sensitivity after 2005

The objective of this paper is to present transient climate simulations of a future in which CO_2 emissions are allowed to continue unabated and geoengineering is used to stabilize global temperatures. We have used an idealized approach in which incoming solar radiation is reduced such that the change in globally averaged absorbed solar radiation is equal but opposite to the radiative forcing from anthropogenic CO_2 (see *Methods*). We used the University of Victoria Earth System Climate Model (UVic ESCM) (10), which is an intermediate complexity global model with explicit representations of ocean circulation and heat uptake, sea–ice dynamics, atmospheric energy and moisture balances, and terrestrial vegetation distributions (see *Methods*). Furthermore, the UVic ESCM includes a prognostic global carbon cycle that allows quantification of the carbon cycle response to geoengineering. We present results from a business-as-usual carbon emissions scenario in which geoengineering is implemented some time between the year 2000 and the year 2075. We also present simulations in which geoengineering is implemented immediately and then terminated abruptly in the future, either as a result of system failure or because of the discovery of unforeseen or unacceptable environmental consequences. Finally, we discuss how current uncertainties in the climate response to anthropogenic forcing could manifest in a geoengineered world (see list of model runs in Table 1).

Results

In the nongeoengineered reference simulation (A2), global temperatures increased by 3.5°C from 1900 to 2100 in response to an atmospheric CO_2 increase from 280 to 880 ppm by volume. The spatial pattern of warming is shown in Fig. 1*a*, with warming ranging from 2.5°C in the southern Pacific to >5°C at high northern latitudes. By contrast, global temperatures at 2100 in the fully geoengineered simulation (GEO) were very close to year-1900 levels, with regional temperature changes varying from −0.35°C in the tropical Pacific to less than +1.0°C in the Arctic (Fig. 1*c*). This distribution of warming and cooling in GEO is the result of a globally uniform factor applied to incoming solar radiation (see *Methods*), which resulted in a greater absolute reduction in incoming solar radiation in the Tropics relative to the poles. As a consequence, there was a small reduction in the equator-to-pole temperature gradient in GEO relative to preindustrial conditions, although this decrease was only about half of the change simulated in the A2 simulation.

Spatial changes in precipitation are perhaps more interesting. In the A2 simulation, globally averaged precipitation decreased slightly by 0.02 mm/day from 1900 to 2100, with increased precipitation over oceans (due to warming) counteracted by decreased precipitation over land (Fig. 1*b*). Land precipitation

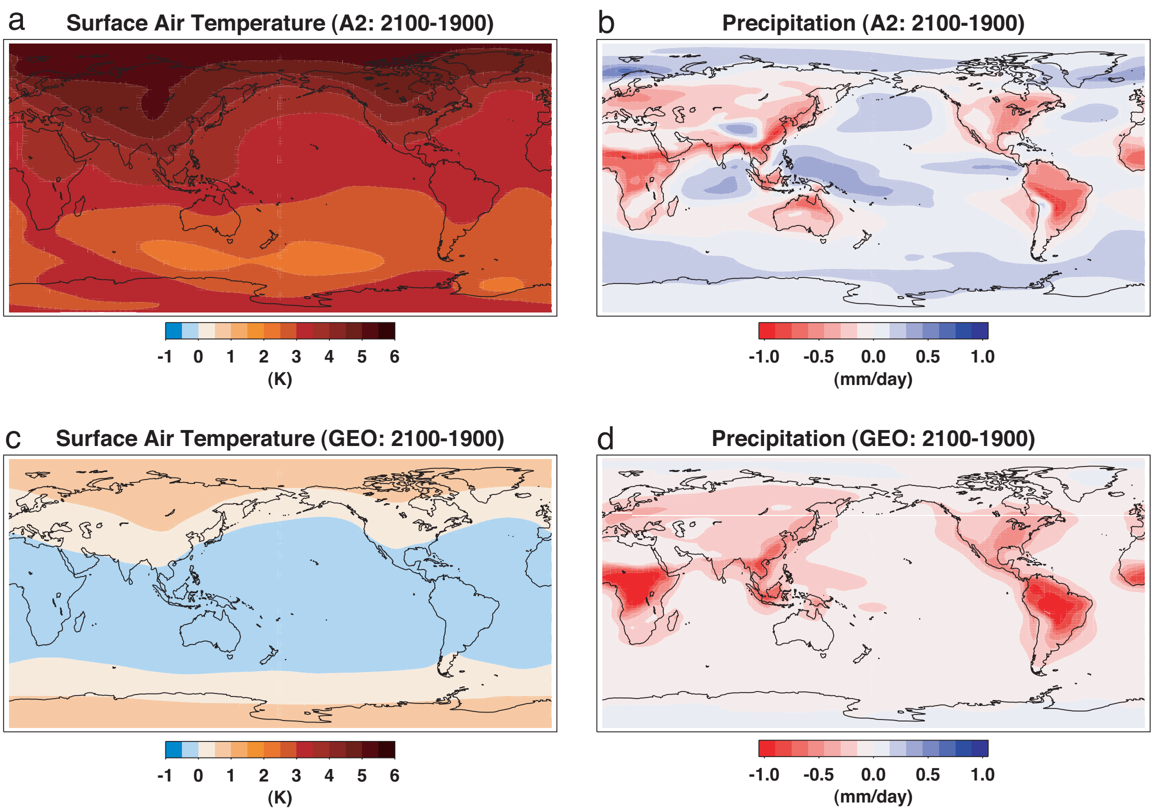

Fig. 1. Simulated changes in surface air temperature (*a* and *c*) and precipitation (*b* and *d*) at 2100 relative to 1900 for model runs A2 (*a* and *b*) and GEO (*c* and *d*). Plots show differences in 10-year averages centered on 2095 and 1895, respectively.

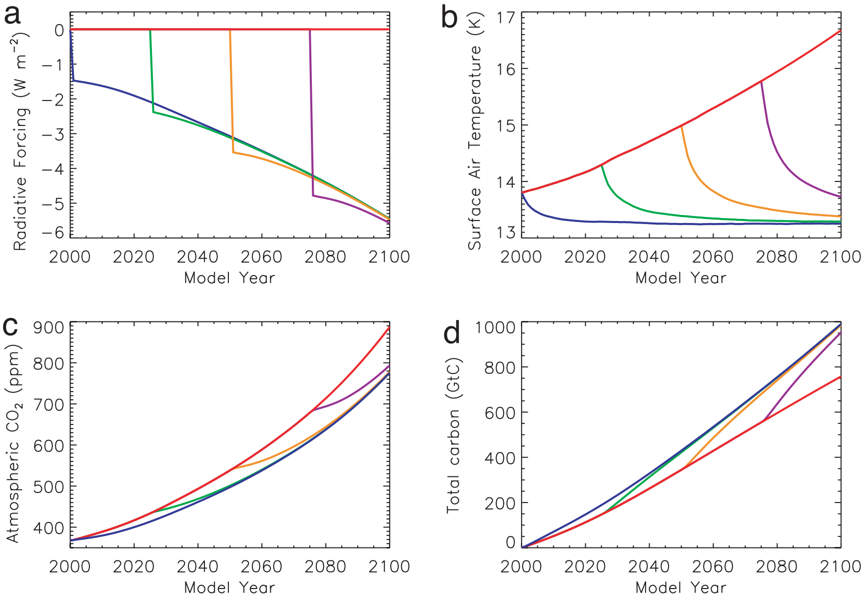

Fig. 2. Prescribed geoengineering radiative forcing (*a*), simulated globally averaged surface air temperature (*b*), simulated atmospheric CO_2 (*c*), and simulated change in combined land and ocean carbon storage (*d*) for runs A2 (red), GEO (blue), ON_2025 (green), ON_2050 (orange), and ON_2075 (purple).

decreases can be explained by the effect of elevated CO_2 on plant photosynthesis, whereby plants use soil water more efficiently and evapotranspiration is reduced in a high-CO_2 world (11). In GEO, however, the atmosphere did not warm appreciably at 2100 relative to 1900; consequently, the direct effect of elevated CO_2 on evapotranspiration was the dominant driver of precipitation changes. Global averaged precipitation decreased by 0.18 mm/day from 1900 to 2100, with the largest regional decreases (up to 1.0 mm/day) over tropical land areas (Fig. 1*d*).

Fig. 2 shows globally averaged geoengineered radiative forcing (Fig. 2*a*) and temperature (Fig. 2*b*) from 2000 to 2100 for runs A2 (red line) and GEO (blue line), in addition to three simulations with geoengineering applied at years 2025 (ON_2025; green line), 2050 (ON_2050; orange line), and 2075 (ON_2075; purple line). For all geoengineering runs, global temperature responded quickly to changes in incoming solar radiation; temperature decreased toward preindustrial temperatures in all cases with an *e*-folding time scale of $\approx$5 years.

Fig. 2*c* shows the simulated atmospheric CO_2 for the same five model runs. The airborne fraction of CO_2 emissions was simulated as a function of terrestrial and oceanic carbon sinks, which themselves evolved in the model as a function of changes in atmospheric CO_2 and climate. In previous model simulations, both terrestrial and oceanic carbon sinks have been shown to increase as a function of atmospheric CO_2 levels, although this increase is offset by climate changes, which tend to reduce carbon uptake (so-called positive climate–carbon cycle feedbacks; see *Methods*) (12). Geoengineering in these simulations tended to return global temperatures toward preindustrial levels; as global temperatures decreased, both terrestrial and ocean carbon sinks became stronger (Fig. 2*d*). As a result, atmospheric CO_2 levels in geoengineered runs were lower: at 2100, atmospheric CO_2 in GEO was 110 ppm by volume (12.5%) lower than in A2. CO_2 levels in ON_2025, ON_2050, and ON_2075 followed the A2 scenario until the onset of geoengineering, at which point they converged with CO_2 levels in GEO as carbon sinks strengthened in response to global cooling. This artificial strengthening of carbon sinks was not permanent, however, and persisted in the model only as long as geoengineering was continued.

This temporary suppression of climate–carbon cycle feedbacks, combined with the rapid adjustment of the climate system to changes in solar forcing, could lead to severe climate consequences in the case of abrupt termination or failure of geoengineering schemes. In runs where geoengineering was stopped abruptly (OFF_2025, OFF_2050, and OFF_2075), global temperatures converged rapidly with the nongeoengineered climate (A2) (Fig. 3*a*). This warming rebound resulted in several years of very rapid climate change, with annual temperature changes reaching 4°C per decade in the case of OFF_2075 (Fig. 3*b*). This

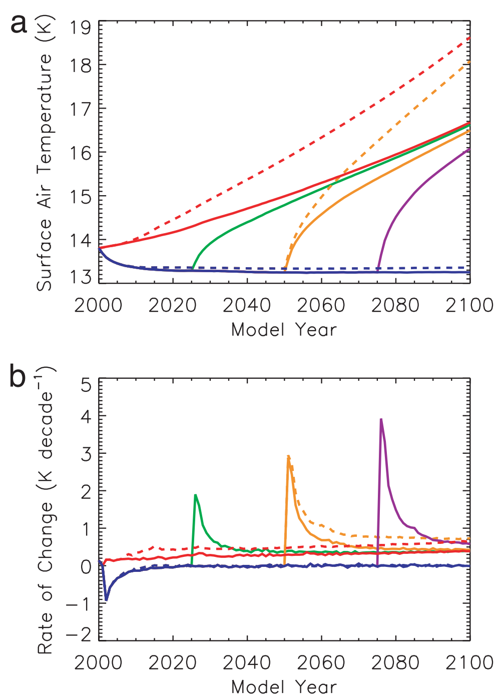

Fig. 3. Simulated surface air temperature (*a*) and annual rate of temperature change (*b*) for runs A2 (red), GEO (BLUE), OFF_2025 (green), OFF_2050 (orange), and OFF_2075 (purple). Runs with doubled climate sensitivity (A2+CS, GEO+CS, and OFF_2050+CS) are plotted as dashed lines.

rate of temperature change is ≈20 times the current rate of climate warming (0.2°C per decade). The peak rate of warming associated with geoengineering failure at 2025 was less (2°C per decade) but still on the order of 10 times the rate of current climate change.

Fig. 3 also shows results from simulations in which climate sensitivity was approximately doubled after the year 2005 (A2+CS, GEO+CS, and OFF_2050+CS; dashed lines). Interestingly, increasing climate sensitivity did not affect the geoengineered radiative forcing required to prevent CO_2-induced warming, because the magnitude of CO_2 forcing was unchanged in the doubled climate sensitivity runs. Therefore, the "effectiveness" of geoengineering in these runs was independent of climate sensitivity. However, in a stabilized climate there is also no way of knowing how large climate sensitivity actually is until geoengineered forcing is removed. These implications of a world with high climate sensitivity are illustrated in Fig. 3. Higher climate sensitivity in OFF_2050+CS resulted in larger and more sustained rapid warming upon failure of geoengineering than in the lower climate sensitivity simulation.

Discussion

Our aim is to quantify some of the potential climatic consequences of using geoengineering as an alternative to CO_2 emissions reductions over the next century. Neglecting technical and scientific uncertainties regarding the deployment and effectiveness of schemes aimed at reducing incoming solar radiation, we have shown here that a uniform reduction of insolation is capable of counteracting most of the regional surface warming resulting from anthropogenic CO_2. This is not true, however, of precipitation changes. Previous studies (8, 9) did not report significant changes in precipitation patterns between geoengineering and control climate simulations; however, these studies did not consider the direct effect of elevated CO_2 on the hydrological cycle via changes in plant water use efficiency. As we have shown here, in the absence of climate warming, elevated CO_2 had a dominant effect on regional precipitation anomalies, with the result that there were large decreases in precipitation over vegetated land surfaces, particularly in the Tropics. This result carries important implications for other aspects of the hydrological system, particularly soil water storage and surface runoff, which have themselves been demonstrated to be affected by the direct effect of elevated CO_2 on evapotranspiration (13).

Because of the rapid response of the climate system to a reduction of incoming solar radiation, there is perhaps little opportunity cost associated with delaying deployment of any geoengineering scheme until it is clear that dangerous climate change is unavoidable by other means. It is also notable that future carbon sinks, as well as feedbacks between climate change and the carbon cycle, play a strong role in affecting how much geoengineering is required to counteract the CO_2 radiative forcing that results from a given emissions scenario. Recent studies have highlighted the large uncertainty in the magnitude of future carbon cycle feedbacks; for example, at the year 2100, simulated atmospheric CO_2 levels have varied by >300 ppm by volume in response to the same CO_2 emissions scenario (12). This large uncertainty is directly relevant to attempts to geoengineer the climate system. If future carbon sinks are stronger (weaker) than anticipated, then the amount of geoengineering required to offset CO_2 emissions will be overestimated (underestimated).

Furthermore, in the event of abrupt failure and/or deliberate termination of geoengineering and some point in the future, carbon sinks will likely weaken as climate warms and positive climate–carbon cycle feedbacks (or uncertain strength) become activated (12). The consequent acceleration of atmospheric CO_2 accumulation in the model runs shown here contributed to the very high rates of temperature change (2–4°C per decade) plotted in Fig. 3 as global climate warmed in response to the unmasking of CO_2 forcing. It is worth emphasizing that the current rate of climate change (0.2°C per decade) is already high relative to reconstructed estimates of rates of paleotemperature changes. Estimates of local warming rates in the northern Atlantic during the Dansgaard–Oeschger events of the last glacial period have been estimated to be in the range of 8–16°C over several decades. However, warming rates in the Antarctic were much smaller (1–3°C on millennial time scales); therefore, there is no evidence that global temperature changes have approached 2–4°C per decade at any time over the last several glacial cycles (14).

Rates of temperature warming of this magnitude, resulting from failed attempts at geoengineering, would likely have severe impacts on both human and environmental systems. Furthermore, the potential for high rates of climate change associated with the onset and/or failure of geoengineering would be even more of a concern should the international coordination of the deployment of geoengineering schemes prove to be challenging. In the case of inconsistent or erratic deployment (either because of shifting public opinions or unilateral action by individual nations), there would be the potential for large and rapid temperature oscillations between cold and warm climate states. It is also likely that such scenarios would lead to uneven spatial application of geoengineering, as opposed to the spatially uniform reduction of solar radiation used in our experiments. Temporally and spatially patchy attempts at geoengineering would pose significant challenges to adaptation by human societies and natural ecosystems.

Current large uncertainties in the climate response to anthropogenic forcing (climate sensitivity) are directly relevant to the question of geoengineering. A world with both rising CO_2 concentration and geoengineered climate stabilization is comparable to an unstable equilibrium held in balance by two opposing forces that grow as a function of time. If climate sensitivity turns out to be on the high end of current estimates [which have not been able to rule out climate sensitivities as large as 8–10°C for a doubling of CO_2 (e.g., ref. 15)], the difference between temperatures resulting from a geoengineered climate and temperatures in the absence of geoengineering would be substantially larger. Furthermore, because the amount of geoengineered forcing required to neutralize a given CO_2 increase is independent of climate sensitivity, there would be no obvious way of predicting the magnitude of the consequences of abrupt geoengineering failure (which depend highly on climate sensitivity).

The suite of possible climatic consequences of geoengineering presented here is by no means exhaustive. Further study is required to determine how atmospheric chemistry and the lifetime of non-CO_2 greenhouse gases might be affected by changes in solar radiative fluxes. There also are unresolved concerns that geoengineering proposals involving sulfate aerosols may have negative consequences for stratospheric ozone levels. There is the potential for additional carbon cycle responses to geoengineering beyond those shown here, such as the effects on biological systems that might result from changes in the partitioning of direct and diffuse radiation. More generally, one of the effects of geoengineering (by design) is to decouple levels of greenhouse gases in the atmosphere from global surface temperatures. These two quantities have been strongly coupled throughout the Earth's recent history (e.g., ref. 16), and it is not clear how biological systems may respond to a change in the global relationship between atmospheric CO_2 and temperature.

Decreasing emissions of greenhouse gases reduces the environmental risk associated with climate change. By contrast, continued CO_2 emissions, even with the potential of geoengineering, will likely increase environmental risk. Thus, with respect to environmental risk, geoengineering is not an alternative to decreased emissions. Opponents of immediate climate mitigation actions might argue for a delay in emission reductions based on a lack of trust in climate model predictions. However, reliance on geoengineering implies a larger trust in climate model results than does reliance on emissions reductions. For example, even if there were only a 50% probability that climate model predictions are approximately correct, reducing emissions could be a prudent avoidance of risk. However, if we had only 50% confidence in climate model predictions of the efficacy of geoengineering schemes, then reliance on geoengineering is likely to be imprudent.

We acknowledge that some proponents of geoengineering have argued that geoengineering would not be a viable alternative to mitigation efforts aimed at reducing greenhouse gas emissions, but rather that it may prove to be a necessary last resort to prevent dangerous changes in the event that future climate warming is larger than anticipated (17). It is possible, however, that increased anthropogenic interference in the climate system (even in the form of geoengineering) could result in a net increase of global impacts on human and environmental systems. As current climate impacts continue to manifest over the next several years, calls for geoengineering fixes to the climate/energy problem may become louder and more widespread. It is critical that the climatic consequences of geoengineering schemes be comprehensively explored before deployment of such schemes are considered. It is equally critical that efforts to mitigate greenhouse gas emissions do not become hampered or slowed by the specter of false certainty in our ability to geoengineer the climate change problem away.

Methods

The climate component of version 2.8 of the UVic ESCM consists of a 19-layer ocean general circulation model coupled to a dynamic–thermodynamic sea–ice model and a reduced-complexity single layer (energy–moisture balance) atmospheric model (10). Horizontal resolution is 1.8° latitude by 3.6° longitude; water, heat, and carbon are all conserved to machine precision without the use of flux adjustments. Land and terrestrial vegetation are represented by a simplified version of the Hadley Centre's MOSES2 land surface model coupled to the dynamic vegetation model TRIFFID (18, 19). Ocean biology was simulated by using a simple NPZD model (20), with air–sea carbon fluxes computed according to the OCMIP abiotic protocol (10, 21); land carbon fluxes were calculated within MOSES2 and were allocated to soil and vegetation carbon pools within the five plant functional types supported by TRIFFID.

The UVic ESCM is a coupled climate–carbon model; as such, carbon cycle feedbacks were simulated interactively by the model. These feedbacks included strengthened ocean and terrestrial carbon uptake due to elevated CO_2 (negative feedback) and opposing positive feedbacks whereby carbon sinks are weakened by climate changes. Simulated processes that contribute to an overall positive climate–carbon cycle feedback included accelerated soil carbon decomposition, decreased tropical vegetation productivity with temperature increases, and the effect of climate warming on ocean carbon solubility, ocean circulation (solubility pump), and biological productivity (biological pump) (see ref. 22).

Radiative forcing in the UVic ESCM is specified as the natural logarithm of simulated atmospheric CO_2 relative to a reference CO_2 concentration (10). Geoengineering was represented by a factor (K_g) applied to incoming solar radiation, computed to satisfy

$$K_g S_{TOA}(1 - \alpha_P) = F \ln \frac{CO_2}{280.0}, \quad [1]$$

where S_{TOA} is the globally averaged top of atmosphere solar flux, α_P is the planetary albedo, and F is a constant equal to 5.35 W/m^2. To balance the radiative forcing from doubled CO_2 required a decrease in incoming solar radiation of 3.7 W/m^2, corresponding to a K_g of ≈0.016. When geoengineering was "on" in a model run, K_g was calculated at each time step to follow increasing atmospheric CO_2, and incoming solar radiation at every grid cell was multiplied by $(1 - K_g)$ such that Eq. **1** was satisfied in the global average. Global temperatures in the model responded to this geoengineered forcing by returning to preindustrial conditions.

Model runs presented in this paper are listed and described in Table 1. All runs were spun up to a near-stationary equilibrium under preindustrial CO_2 and then driven by observed CO_2 concentrations (23) to the year 2000. From 2000 to 2100, CO_2 emissions from fossil fuels and land-use change were specified from the Special Report on Emissions Scenarios A2 scenario (24). Other climate forcings, both anthropogenic (non-CO_2 greenhouse gases and land cover change) and natural (insolation and volcanic aerosols) were neglected in these simulations. Geoengineering was applied to or removed from a simulation instantaneously.

We also performed a set of runs to analyze the effect of climate sensitivity uncertainty on the predicted climate system response to geoengineering. In these runs (A2+CS, GEO+CS, and OFF_2050+CS), climate sensitivity was modified after the year 2005 by means of an adjustable temperature–longwave radiation feedback:

$$L^*_{out} = L_{out} - K_{LW}(T - T_0), \quad [2]$$

where L_{out} is the unmodified outgoing longwave radiation and L^*_{out} is the new outgoing longwave radiation reduced at each time step as a function of the difference between globally averaged surface air temperature and the equilibrium preindustrial temperature $(T - T_0)$. This parametrization was chosen based on a formulation of climate sensitivity as the sum of the response to direct CO_2 forcing and net effect of climate feedbacks. Eq. **2** serves to increase the net climate feedback by damping the increase in outgoing longwave radiation with increased surface temperature (mimicking, for example, a strong positive cloud feedback). The value of the constant parameter K_{LW} was selected such that the equilibrium climate sensitivity (the global temperature response to doubled CO_2 after >2,000 years of model integration) was approximately doubled.

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