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Climate engineering and the risk of rapid climate change

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Abstract

Recent research has highlighted risks associated with the use of climate engineering as a method of stabilizing global temperatures, including the possibility of rapid climate warming in the case of abrupt removal of engineered radiative forcing. In this study, we have used a simple climate model to estimate the likely range of temperature changes associated with implementation and removal of climate engineering. In the absence of climate engineering, maximum annual rates of warming ranged from 0.015 to 0.07 °C/year, depending on the model's climate sensitivity. Climate engineering resulted in much higher rates of warming, with the temperature change in the year following the removal of climate engineering ranging from 0.13 to 0.76 °C. High rates of temperature change were sustained for two decades following the removal of climate engineering; rates of change of 0.5 (0.3, 0.1) °C/decade were exceeded over a 20 year period with 15% (75%, 100%) likelihood. Many ecosystems could be negatively affected by these rates of temperature change; our results suggest that climate engineering in the absence of deep emissions cuts could arguably constitute increased risk of dangerous anthropogenic interference in the climate system under the criteria laid out in the United Nations Framework Convention on Climate Change.

Keywords: geoengineering, climate engineering, rapid climate change, dangerous anthropogenic interference

1. Introduction

It has become evident in recent years that efforts to reduce greenhouse gas emissions through international policies, like the Kyoto Protocol, have fallen far short of reaching their goals (Raupach *et al* 2007). Many of the outlined emissions targets that have been set in place for some time now, in several international frameworks, are very far from being attained. These continued sluggish efforts to mitigate climate change in conjunction with the increasing evidence that suggests our planet may be closer to unsafe levels of anthropogenic climate change than previously anticipated (Hansen 2005), have prompted numerous climate scientists to look towards an alternate solution to the impending problem. As a result, there has been recent renewed interest in direct climate intervention or geoengineering as a possible means to offset greenhouse-gas-induced climate change (Crutzen 2006).

Geoengineering is defined as the, '... intentional large-scale manipulation of the environment ...' to counteract anthropogenic climate change (Keith 2000). Some proposed geoengineering schemes include: atmospheric scatters (sulfate injections into the stratosphere), space-based scatters, land surface albedo modifications, ocean fertilization, carbon capture and sequestration (Keith 2000). Climate engineering refers more specifically to those schemes, which are aimed at decreasing incoming solar radiation. Previous modeling studies showed that geoengineering schemes could effectively stabilize global temperatures, albeit with some regional variability in effectiveness (Govindasamy and Caldeira 2000). It has also been suggested that a combined approach of emissions reduction and geoengineering could create an optimal economic strategy for solving the problem of climate

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change (Wigley 2006). Typically, geoengineering schemes aim to avert catastrophic climatic impacts thus reducing the risks of dangerous climate change. However, geoengineering carries its own risks. For example, Trenberth and Dai (2007) and Bala *et al* (2008) identified possible impacts of albedo geoengineering on the hydrological cycle, and Tilmes *et al* (2008) showed that stratospheric ozone could be affected by stratospheric sulfate aerosol injection. Matthews and Caldeira (2007) showed that in the case of an abrupt termination of geoengineering, there would be the potential for very rapid warming as climate re-adjusts to high greenhouse gas levels in the atmosphere without the countervailing influence of geoengineering.

In this study, we focus on the potential for rapid climate change associated with geoengineering. The importance of the rate of temperature change (in addition to the amount of change) was recognized in the Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC). According to this Article:

'The ultimate objective of this Convention ... is to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved *within a time frame sufficient to allow ecosystems to adapt naturally to climate change ...*' (emphasis added) (UNFCCC 1992).

While this statement does not explicitly define what constitutes 'dangerous' climate change, it can be inferred that both the absolute magnitude of climate change (as determined by the greenhouse gas stabilization level) and the rate of climate change (as determined by the time frame over which stabilization is achieved) can contribute to the possibility of dangerous anthropogenic interference in the climate system.

In this study, we highlight the relationship between geoengineering and rapid climate change by quantifying the risk of abrupt temperature change in a scenario where climate engineering is used to stabilize temperatures in the context of business as usual (BAU) greenhouse gas emissions. In particular, we estimate the likelihood of rapid temperature change following the removal (or failure) of climate engineering technologies. We compare our estimated rates of temperature change with available estimates of ecosystem resiliency to the rate of climate change, and argue, based on this analysis, that geoengineering could in fact contribute to increased risk of dangerous anthropogenic interference in the climate system, as defined by the UN Framework Convention on Climate Change.

2. Methods

In this study we use the MAGICC (Model for the Assessment of Greenhouse-gas-Induced Climate Change) climate model to quantify the effects of the implementation and subsequent removal of climate engineering on the climate system. MAGICC is a set of coupled gas cycle, climate and ice-melt models, which allows the user to determine the global mean temperature and sea-level responses to user-specified greenhouse gas and sulfur dioxide emissions. The MAGICC model is described in detail in Wigley *et al* (2000) and is one of the primary models used in the IPCC reports to project future global mean temperature and sea-level rise. We applied geoengineering in the MAGICC model as follows: net radiative forcing values from greenhouse gases and aerosols were obtained by running the model under a mid-range business as usual emissions scenario (AIB). In a second simulation, geoengineering was implemented as a specified forcing of equal magnitude (but opposite sign) to the forcing from anthropogenic greenhouse gases and aerosols. This geoengineering forcing was applied in the year 2020 and removed in 2060. These paired business as usual and geoengineering simulations were repeated approximately 40 times each, varying the climate sensitivity of MAGICC from 0.5 to 10 °C.

We used the estimated climate sensitivity probability density function from Hegerl *et al* (2006) to assign likelihood values to each set of model simulations.

Climate sensitivity is defined as the equilibrium response of global mean surface air temperature to a doubling of the carbon dioxide concentration (Meehl *et al* 2007). According to the IPCC FAR (Fourth Assessment Report), equilibrium climate sensitivity is likely to lie in the range 2–4.5 °C, with a most likely value of 3 °C. Hegerl *et al* (2006) estimated a likely range of climate sensitivity of between 1.5 and 6.2 °C, with a most likely value of 2.5 °C; we take this estimate to be broadly representative of the range of climate sensitivity probability distributions presented in Meehl *et al* (2007), though note that the specific values we report here are dependent on this choice of climate sensitivity probability distribution.

The emissions scenario used in all of the model simulations was taken from the IPCC SRES (special report on emissions scenarios) library and is called A1B-AIM (Nakicenovic *et al* 2000). According to the report, the A1B scenario group assumes a 'balanced' approach in the future, in which there are no technologies that gain an overwhelming advantage. This scenario group includes the A1B marker scenario developed using the AIM model. In the A1B-AIM marker scenario, the global average per capita energy demand grows from 54 GJ in 1990 to 247 GJ in 2100 (IPCC 2007). Throughout this time carbon intensity declines relatively slowly until 2050, which results in a rapid increase in carbon dioxide emissions in the first decades of the century. However, after 2050, when the balanced structural changes in the energy sector begin to take effect, carbon intensity drops quickly. The overall result is that growing energy demands from an increasing prosperous population is offset and carbon emissions decline between the years 2050 and 2100 (IPCC 2007). It should also be noted that this mid-century drop in carbon intensity can be seen as a decrease in the rate of temperature between 2040 and 2050 in figure 2(a).

3. Results

Figure 1 shows the temperature change with respect to the year 1990 for the business as usual scenario (BAU) and the case where climate engineering was applied from 2020 to 2059. With no climate engineering, temperature increased consistently throughout the 21st century; temperature increases from 1990 to 2100 ranged from 0.6 to 5.1 °C for climate

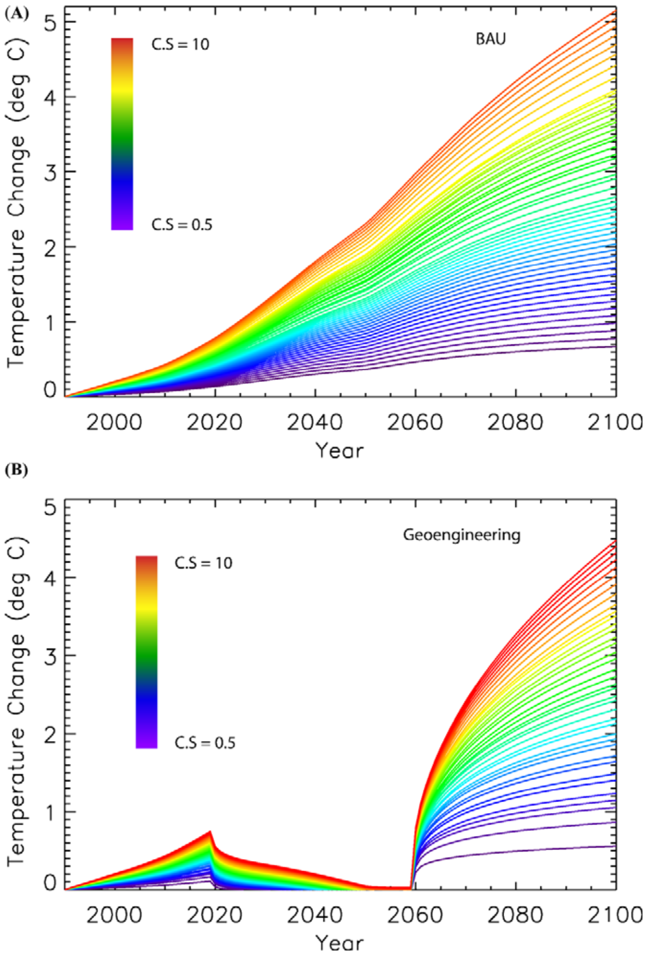

Figure 1. Temperature change with respect to the year 1990 for the business as usual scenario (BAU) (A), and the case where geoengineering is applied from 2020 to 2059 (B). Each line represents a different climate sensitivity as indicated in the color bar.

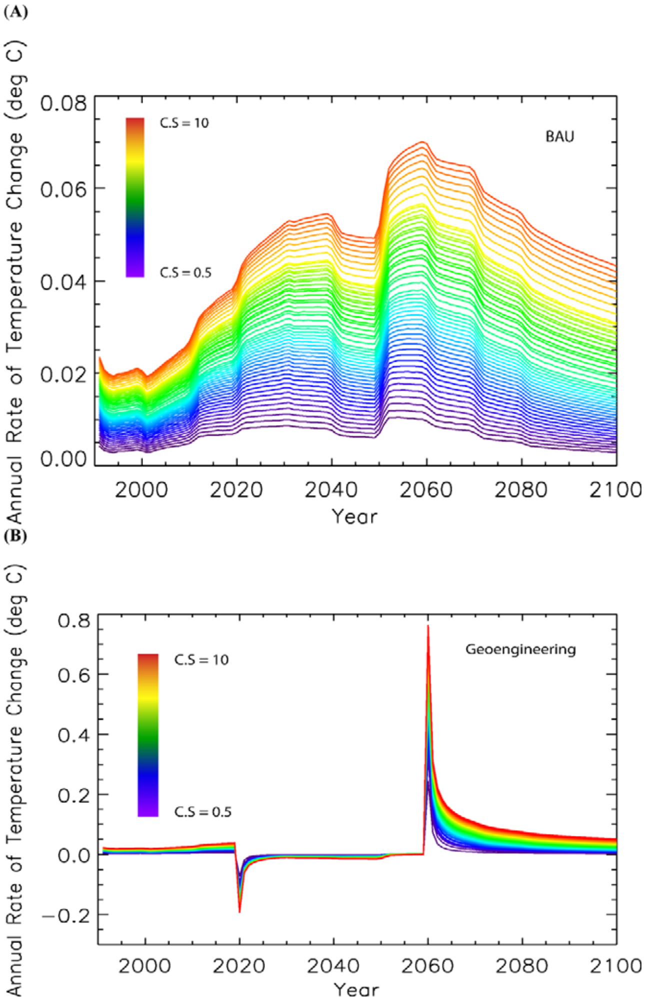

Figure 2. Annual rate of temperature change for the business as usual scenario (BAU) (A), and the case where geoengineering is applied from 2020 to 2059 (B). Each line represents a different climate sensitivity as indicated in the color bar.

sensitivities from 0.5 to 10 °C. CO_2 concentrations at the year 2100 varied from 690 to 739 ppmv, where higher climate sensitivities led to slightly higher CO_2 concentrations due to the effect of positive climate carbon cycle feedbacks. In the climate engineering simulations, temperatures returned close to year-1990 temperatures between 2020 and 2059. When the engineered forcing was removed temperatures increased abruptly towards a level consistent with atmospheric greenhouse gas concentrations. Furthermore, the temperature change following the removal of climate engineering increased with higher values of climate sensitivity yielding a temperature change between 0.15 and 4.5 °C between 2060 and 2100. The final CO_2 concentrations in the geoengineering runs were comparable to those in the BAU simulations (between 689 and 722 ppmv).

Figure 2 shows the annual rate of temperature change between 1990 and 2100 for each set of simulations. In the BAU ensemble (figure 2(A)) the annual rate of temperature change increased steadily until the year 2060, after which greenhouse gas emissions decline in the A1B emissions scenario (Nakicenovic *et al* 2000) leading to a decreased rate of temperature change. In the climate engineering runs (figure 2(B)), the rate of temperature change was small up to the year 2020, whereupon temperatures decreased following the abrupt implementation of geoengineering. The rate of temperature change was negligible up until 2060, at which point temperatures increased very abruptly in response to the removal of climate engineering. The maximum rate of warming varied from 0.13 to 0.76 °C/year, though these very high rates of warming were not sustained for more than a few years; within a decade, rates of temperature change had decreased to less than 0.1 °C/year. The maximum rate of sea-level rise in the geoengineering simulations was also higher than in the BAU simulations (not shown), though the difference was less extreme on account of the slower response time of ocean temperatures to external forcing.

Figure 3(A) shows the probability density functions for the maximum annual temperature change between 1990 and 2100. For the business as usual (BAU) simulation the most likely maximum annual temperature change was only 0.031 °C/year. In the geoengineering simulation the most likely maximum rate of temperature change was just under 0.5 °C/year, occurring in the year 2060. Figure 3(B) shows the probability density functions for the maximum decadal rate of global mean

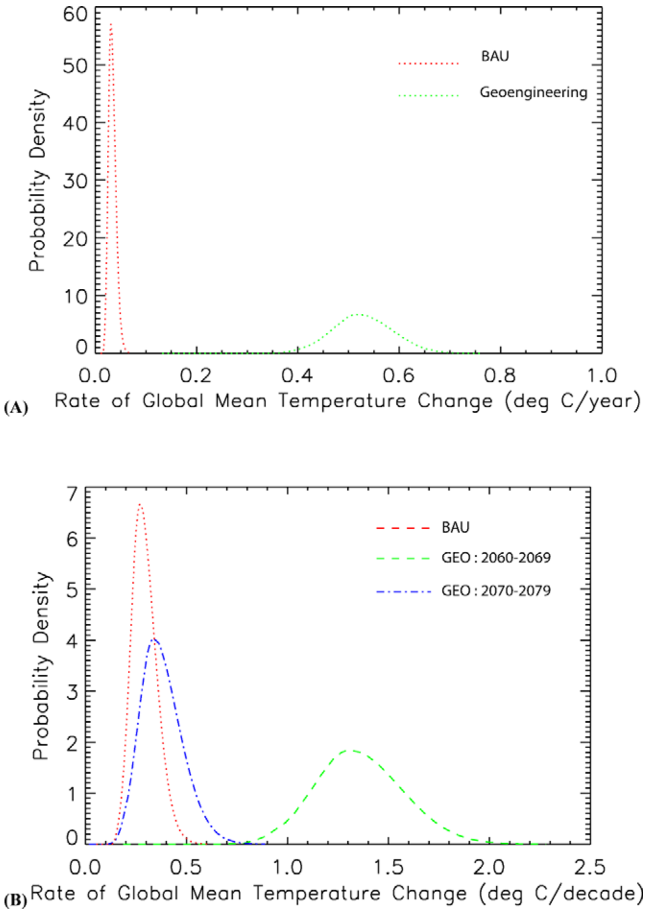

Figure 3. Probability density functions for the maximum annual rate of global mean temperature change (A) and for decadal rates of global mean temperature change (B) between 1990 and 2100. Decadal temperature changes represent the maximum decadal rate in the BAU simulations (red line), and temperature changes during the first (green line) and second (blue line) decades following the removal of geoengineering.

temperature change. The highest decadal temperature changes occurred immediately following the termination of climate engineering (2060–2069), with rates ranging from 1.0 to 1.7 °C/decade (5–95% confidence interval), and a most likely rate of 1.3 °C/decade. By the second decade (2070–2079), the most likely warming rate had decreased to 0.33 °C/decade (5–95% confidence interval: 0.28–0.55 °C/decade), slightly higher than the most likely decadal warming in the BAU simulations (0.29 °C/decade; 5–95% confidence interval 0.2–0.41 °C/decade).

Figure 4(A) shows the probability of exceeding a given rate of annual temperature change. In the climate engineering simulations (green line) there was a 65% probability of exceeding a rate of 0.5 °C/year; for the same rate of warming in the business as usual simulation (red line) the probability of exceeding was 0%. Figure 4(B) shows the probability of exceeding a given decadal rate of global mean temperature change. In the first decade following the removal of climate engineering (2060–2069: green line) there was a 96% probability of exceeding 1 °C warming, and a 25% probability of exceeding 1.5 °C. In the second decade (2070–2079: blue line) the probability of exceeding 0.5 (0.3, 0.1) °C warming per decade, was 15% (75%, 100%). In the BAU simulations, these same thresholds (1.0, 0.3, 0.5, 0.1 °C/decade) were exceeded with 0, 1.5, 42.5 and 100% likelihood, respectively.

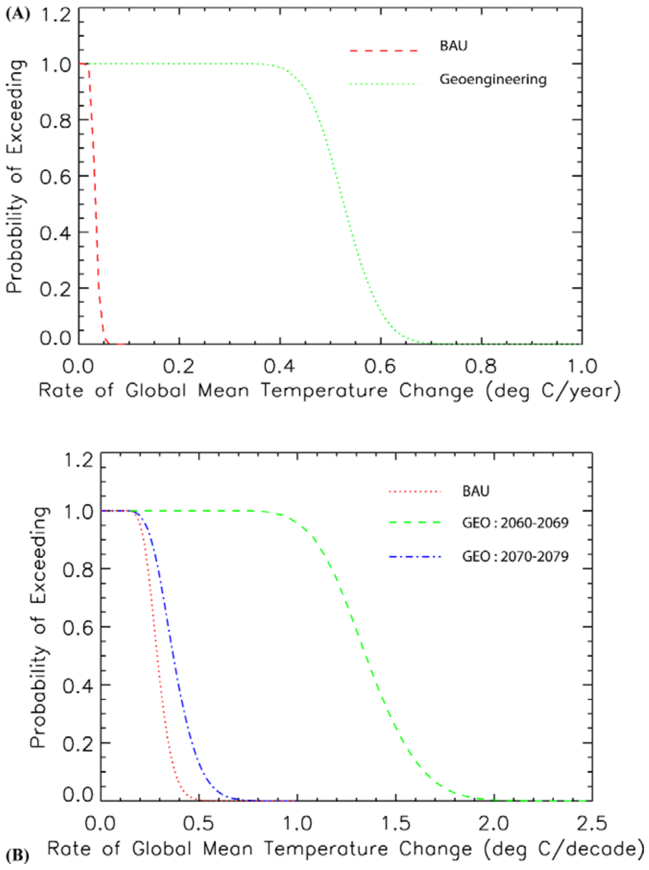

Figure 4. Probability of exceeding the maximum annual rate of temperature change (A) and decadal rates of temperature change (B) between 1990 and 2100. Decadal temperature changes represent the maximum decadal rate in the BAU simulations (red line), and temperature changes during the first (green line) and second (blue line) decades following the removal of geoengineering.

4. Discussion

In this letter, we showed that the use of planetary-scale geoengineering carries a risk of rapid climate change in the case of its abrupt removal or sudden failure. The sustained high rates of warming in these simulations could have serious environmental impacts on many biomes and natural systems, and could compromise the ability of ecosystems to ‘adapt naturally to climate change’ as required by the UNFCCC.

No consensus exists in the literature as to what rate of climate change could result in dangerous ecosystem impacts. The Summary for Policymakers of the IPCC’s *Fourth Assessment Report* stated clearly that the magnitude and timing of impacts that will ultimately be realized depends both on the amount and the rate of climate change (IPCC 2007). Vliet and Leemans (2006) assessed the ecological impacts of climate change on various biomes in response to different ranges of rates of temperature change. For example, Vliet and Leemans (2006) stated that a warming rate greater than 0.1 °C/decade would threaten most ecosystems and decrease their ability to adapt naturally. The proposed rate of temperature increase of 0.05 °C/decade is a threshold to protect ecosystems; above this amount, ecosystem damage is increasingly likely to occur. The authors argued that with increasing rates of change there would be progressively more ecosystem loss, increased ecosystem vulnerability, decreased biodiversity and aggressive opportunistic species dominance across the globe.

In a similar study, Leemans and Eickhout (2004) looked at rates of climate change based on global mean temperature in 2100 and used ecosystem shifts as the major impact indicator. They found that at a rate of warming of 0.1 °C/decade, 50% of all impacted ecosystems are able to adapt within a century but only 36% of all impacted forests adapt within the same time frame. As the rate of change increased the adaptive capacity of ecosystems rapidly decreased. For example, at a rate of 0.3 °C/decade, only 30% of all impacted ecosystems and only 17% of all impacted forests would be able to adapt (Leemans and Eickhout 2004). Higher rates lead to degraded ecosystems and consequently, impact carbon storage reservoirs and economic sectors that depend heavily on healthy functional ecosystems (Leemans and Eickhout 2004). These thresholds were exceeded with high probability in both the BAU and climate engineering simulations. However, the climate engineering scenarios resulted in much higher rates of warming, with rates of temperature change returning only to levels comparable to the maximum rates in the BAU simulations two decades after the forcing was removed.

High rates of warming associated with climate engineering could also affect marine ecosystem functions. Abrupt climate change has been linked to overall reductions in marine ecosystem biodiversity through selection for mobile or opportunistic species. Yasuhara *et al* (2008) investigated the deep-sea fossil record of benthic ostracodes during periods of rapid climate change to determine its impact on deep-sea ecosystems. Their results demonstrated that ecosystem community collapses coincided with abrupt changes in the deep-ocean circulation and climate changes and that abrupt climate changes had a direct effect on the surface primary production of food source for benthic species. Similarly, Aoyama *et al* (2008) showed that biodiversity and plankton community dynamics were significantly altered due to abnormally high rates of surface air temperature change in their study area. The apparent shift in phytoplankton community structure coincided with the largest warming rate (0.6–1.0 °C/decade) observed in the historical data for this particular geographic region in Japan, called the Kuroshio stream. These rates of warming were comparable to the temperature changes we simulated in the first decade following the removal of climate engineering (1.0–1.7 °C/decade).

There are indications right now that suggest that the movement of plant species to higher elevations and latitudes is occurring and large-scale adaptation is already underway for many species across the globe (Jump and Penuelas 2005). However, when compared with reported rates of past migrations of plant species, the current rapid rate of climate change has the potential to exceed the adaptive capacity of many species. High rates of warming associated with climate engineering would likely exacerbate this problem. Furthermore, Jump and Penuelas (2005) showed migration rates among different species diverge greatly between different plant species, leading to the formation of novel plant communities. Current differentiations of populations in relation to climate demonstrate the strong selective pressures that climate asserts on natural populations (Jump and Penuelas 2005). Although inter-annual variability is a common phenomenon and is a normal occurrence, such short-term variability is tolerated through phenotypic plasticity. When rates of climate change exceed the threshold of phenotypic plasticity, distributional and evolutionary changes become increasingly likely. An important question is whether the rates of warming following the removal of climate engineering would be short-term enough to be tolerated. It seems likely that two decades of very high rates of warming would be sufficient to severely stress the adaptive capacity of many species and ecosystems, especially if preceded by some period of engineered climate stability.

In this study, we have considered a hypothetical on/off geoengineering scenario in which climate engineering was both implemented and removed abruptly. This is clearly an extreme case and the risks we have reported here of rapid climate warming could be substantially mitigated by a more gradual implementation and decommissioning of climate engineering technology. However, one can imagine scenarios in which abrupt removal of geoengineered climate forcing may be unavoidable, either due to technological failure, or due to the emergence of unforeseen negative impacts of climate engineering. Even in an extreme case of abrupt termination of geoengineering, the risk of rapid climate change could also be decreased by successfully mitigating greenhouse gas emissions during the period of climate engineering. In this case, it becomes critically important to what extent greenhouse gas emissions are decreased in the coming decades, and also to what extent the successful application of climate engineering may affect other mitigation efforts. Clearly, a case where the perceived success of geoengineering leads to decreased incentive to decrease greenhouse gas emissions would represent a potentially dangerous situation of increasing geoengineering dependence to avoid the risk of rapid climate warming that we have reported here.

We note also that the specific warming rates and probabilities we reported here are dependent on both our choice of emission scenario (A1B) and our choice of probability density function for climate sensitivity (Hegerl *et al* 2006). In addition, we considered only climate sensitivity uncertainty and not additional uncertainty associated with ocean heat uptake, natural and anthropogenic forcings or carbon cycle feedbacks. These additional uncertainties would affect the transient climate response of the model, and may therefore affect the decadal-scale rates of temperature change we have reported. In addition, the MAGICC model is a simple one dimensional climate model that does not fully represent the timescales of ocean circulation and heat uptake changes; as a result, the temperature response to the abrupt removal of climate engineering that we have reported may be both somewhat faster and also less sustained than what would be simulated by a more sophisticated ocean model. These additional uncertainties are non-negligible (Forest *et al* 2006, Matthews and Keith 2007, Meehl *et al* 2007) and would invariably change the specific numbers provided here. However, our intent here was not to conduct a full probabilistic assessment of all relevant uncertainties, but rather to highlight the order-of-magnitude risks associated with geoengineering and rapid climate change. The general conclusions we presented here are robust, and would hold in a more comprehensive probabilistic analysis.

5. Conclusion

In this study we used a hypothetical scenario of business as usual greenhouse gas emissions, in which geoengineering was implemented at the year 2020, and removed abruptly after 40 years. By varying the climate sensitivity of the MAGICC model, and using previously published estimates of climate sensitivity likelihoods, we derived a probability distribution for the rate of temperature change following the removal of geoengineering. Our analysis showed that abrupt termination of climate engineering would carry substantial risk of very high rates of warming, which would likely exceed the maximum rate of warming under a business as usual emissions scenario for up to 2 decades after termination.

Studies of ecosystem sensitivity to temperature change suggest that species extinctions and ecosystem collapses are possible consequences of very rapid climate changes. The adaptive capacity of these ecological systems are sensitive to the rate at which temperature changes, and could be affected readily by the risk of high rates of temperature changes associated with climate engineering. In addition to the potential impacts on ecological systems we outlined here, there would clearly be significant impacts on human systems with associated large economic damages from such rates of climate changes (Goes *et al* 2009). These findings suggest that the use of planetary-scale geoengineering carries its own risk of dangerous anthropogenic interference in the climate system, as defined by the UN Framework Convention on Climate Change, which must be weighted against the risks of unmitigated climate change.

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