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Geoengineering by stratospheric SO_2 injection: results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE

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Abstract

We examine the response of the Met Office Hadley Centre's HadGEM2-AO climate model to simulated geoengineering by continuous injection of SO_2 into the lower stratosphere, and compare the results with those from the Goddard Institute for Space Studies ModelE. The HadGEM2 simulations suggest that the SO_2 injection rate considered here ($5\,Tg[SO_2]\,yr^{-1}$) could defer the amount of global warming predicted under the Intergovernmental Panel on Climate Change's A1B scenario by approximately 30–35 years, although both models indicate rapid warming if geoengineering is not sustained. We find a broadly similar geographic distribution of the response to geoengineering in both models in terms of near-surface air temperature and mean June-August precipitation. The simulations also suggest that significant changes in regional climate would be experienced even if geoengineering was successful in maintaining global-mean temperature near current values.

1 Introduction

Over the last decade, global warming has been well documented in both observational records and in simulations with climate models (IPCC, 2001, 2007). Furthermore, scenarios of unmitigated ("business as usual") future climate with these models suggest an increasingly rapid global-mean warming over the next century. The primary cause of global warming is from increased atmospheric concentrations of greenhouse gases (GHG) such as carbon dioxide, methane and nitrous oxide, as a result of anthropogenic activity. These gases exert a positive radiative forcing of climate and hence induce a warming. Increases in concentrations of aerosols are thought to ameliorate the effects of global warming via their impacts on radiation (direct effects) and on clouds (indirect effects), whereby they exert a negative radiative forcing of climate and hence induce a cooling (e.g., Haywood and Schulz, 2007). Recently, these cooling effects from aerosol have been suggested as potential geoengineering mechanisms to counterbalance the effects of global warming.

The impact of brightening stratocumulus clouds via injection of cloud condensation nuclei into low-level stratocumulus clouds has been investigated by Jones et al. (2009) using one of the models used in the present study. They suggest that, although the global-mean warming from increased GHG concentrations can indeed be reduced, there are significant geographical changes in temperature and precipitation patterns which could have adverse effects on some regions of the Earth such as Amazonia. The impact of the injection of sulfur dioxide (SO_2) into the stratosphere has also received much attention, formerly through the eruption of volcanos with large stratospheric sulfate injections (e.g., Robock, 2000) and latterly through deliberate geoengineering (e.g., Rasch et al., 2008; Robock et al., 2008). Once again, the potential non-uniformity of the response to the geoengineering is highlighted. Here we examine the response of two climate models to geoengineering by injection of SO_2 into the lower stratosphere. The two models used are the Met Office Hadley Centre's HadGEM2-AO and the National Aeronautics and Space Administration Goddard Institute for Space Studies ModelE.

HadGEM2-AO is the fully-coupled atmosphere-ocean version of the Hadley Centre Global Environment Model version 2 (Collins et al., 2008). The atmosphere has a horizontal resolution of 1.25° latitude by 1.875° longitude, with 38 vertical levels. This is coupled to a 40-level ocean/sea-ice model with a zonal resolution of 1° and meridional resolution of 1° from the poles to 30°, thereafter varying smoothly to 1/3° at the equator. The sulfate aerosol scheme is described in Jones et al. (2001) and Bellouin et al. (2007).

ModelE is also a coupled atmosphere-ocean model. The stratospheric version of the model was used (Schmidt et al., 2006), which has a horizontal resolution of 4° latitude by 5° longitude with 23 vertical levels. This is coupled to a 13 level ocean model with the same horizontal resolution (Russell et al., 1995). The aerosol module of Koch et al. (2006) is used for SO_2 conversion, transport and removal.

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2 Experimental design

The experimental designs were somewhat different for the two models, but are sufficiently similar for a comparison to be useful. The ModelE simulations are a subset of those reported in Robock et al. (2008). They comprise (i) a 3-member ensemble following the IPCC A1B scenario (Nakićenović et al., 2000) run for 40 years from 1999; (ii) another 3-member A1B ensemble plus geoengineering by SO_2 injection at a point over [0° N, 120° E] into the tropical lower stratosphere (ca. 16–23 km altitude) at a constant rate of 5 Tg[SO_2] yr^{-1} for the first 20 years, after which geoengineering is terminated and the simulation continued for a further 20 years; and (iii) a 2-member Control ensemble run in perpetual 1999 conditions for 40 years. As the variability between members is small (Robock et al., 2008) only the ensemble means are used. The presentation of results from ModelE follows that in Robock et al. (2008) in showing the difference from the perpetual 1999 Control simulation, to minimise the effect of any climate drift.

Three HadGEM2 simulations were performed, following on from a 20th century simulation using historical forcings: A1B and A1B-plus-geoengineering simulations, each of 60 years duration, and also a third simulation where SO_2 injection was suspended after 25 years. A more idealized approach was taken to simulating the geoengineering by using a globally uniform injection of SO_2 into the lower stratosphere at altitudes similar to that in the ModelE simulations, at the same rate of 5 Tg[SO_2] yr^{-1}. The fact that poleward transport of stratospheric aerosol in ModelE is a little too fast (Robock et al., 2008) furthers the general similarity of the two approaches. Tests show that, for the constant SO_2 injection rate applied here, the stratospheric aerosol burden stabilises after 3–4 years, yielding an increase in global mean aerosol optical depth of 0.05 at a wavelength of 550 nm.

As the ModelE simulations only included SO_2 injection for the first 20 years, the comparison will generally focus on the mean difference between the A1B-plus-geoengineering and A1B simulations over the second decade (years 11–20 inclusive)

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for each model.

3 Results

3.1 Solar radiation

Figure 1 shows the zonal-mean distribution of the change in downward surface shortwave radiation ($SW_{\downarrow}$) caused by geoengineering, averaged over the second decade for both models. The distributions are broadly similar in structure, but with ModelE generally having more negative values than HadGEM2 (annual global means are $-2.2\,\mathrm{Wm}^{-2}$ and $-1.1\,\mathrm{Wm}^{-2}$, respectively). There is rather more variability in the results from HadGEM2, probably because the results are from single simulations rather than small ensembles as with ModelE. The fact that there are some positive values in the HadGEM2 simulations is because the change in $SW_{\downarrow}$ is the difference between parallel simulations (with and without geoengineering) which evolve with different meteorology, cloud distributions etc. This is not the case in ModelE, where the change in $SW_{\downarrow}$ was determined by a double-call to the radiation scheme. The cloud response in HadGEM2 is the primary cause of the increases in $SW_{\downarrow}$ at 80° N, 10° N and 60° S, as shown by the decreases in cloud at these latitudes denoted by the dashed line in Fig. 1. That the same injection rate of SO_2 gives different changes in $SW_{\downarrow}$ is due to the different distributions of SO_2 injection (point vs. uniform), different optical properties of the resulting aerosol, and different feedback characteristics of the two models.

3.2 Surface air temperature

Figure 2 shows the evolution of global annual-mean near-surface air temperature anomaly in HadGEM2 (Fig. 2a) and ModelE (Fig. 2b). The full impact of stratospheric SO_2 injection on temperature appears to be realised in both models after the first ten years, with mean cooling rates of -0.74 and $-0.47\,\mathrm{K\,decade}^{-1}$ in HadGEM2 and ModeIE, respectively, over the first decade. This is quite a dramatic rate of temperature change, although it should be borne in mind that this is due to our idealised experimental design where geoengineering is not phased-in but is instead instantaneously fully activated. Both models show a mean temperature change due to geoengineering of about −0.7 K in the second decade relative to their corresponding A1B scenarios (−0.74 K in HadGEM2, −0.69 K in ModelE).

When geoengineering is terminated the sulfate aerosol burden returns to its unperturbed state after about 5 years in HadGEM2 and global mean temperature increases at an average rate of 0.77 K decade^{-1}, returning to the A1B value after about 15 years. This rate of warming is more than twice that in A1B (0.34 K decade^{-1} over years 20–60). The behaviour of ModelE is somewhat different, warming strongly at 1.01 K decade^{-1} for the first 7 years or so, after which the rate of warming reduces to approximately 0.27 K decade^{-1} as it slowly approaches A1B temperatures. These rates compare with a mean warming of 0.16 K decade^{-1} in A1B over the whole period. The results from HadGEM2 shown in Fig. 2a suggest that a given amount of warming under the A1B scenario may be delayed by some 30–35 years by the SO_2 injection rates considered here.

Figure 3a and b show the distribution of near-surface temperature change averaged over the second decade in HadGEM2 and ModelE, respectively. This shows cooling more or less globally in both models, with the strongest cooling at higher northern latitudes. The cooling is generally stronger over land than over ocean in both models, but HadGEM2 also shows cooling over the Arctic which is much stronger than that in ModelE. However, a problem has since been identified with the sea-ice scheme in the ModelE simulations of Robock et al. (2008) analysed here, which resulted in sea-ice being less responsive to temperature changes than it should be. This explains the differences with HadGEM2 at high latitudes, and would also contribute to the lower climate sensitivity of ModelE compared with HadGEM2.

The main thing to note is that, with the exception of extreme northern latitudes, the temperature response of the two models is in reasonable agreement in both magnitude

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and spatial pattern, with HadGEM2 showing a more detailed geographic pattern due to the higher resolution of the model and the fact that it is a single model experiment rather than a small ensemble.

One definition of the goal of geoengineering could be to avoid any further global warming due to continuing increases in GHG concentrations. Figure 2a shows that after about 30 years of the geoengineering simulation the global-mean near-surface air temperature in HadGEM2 is about the same as at the start of the simulation, i.e. the same as the mean 1990–1999 period. It is therefore instructive to examine the mean changes for the 10-year period over which the mean temperature anomaly is approximately zero (mean of years 29–38 inclusive), which period one could consider as being an analogue for geoengineering counterbalancing global warming. The changes in temperature are shown in Fig. 3c for HadGEM2. Although the global-mean temperature change may be near zero (+0.01 K), regionally this is far from the case. Some land areas such as central Africa and Australia are cooler than the 1990–1999 mean by up to 1 K, whereas the Amazon region is warmer by a similar amount. Polar amplification due to ice-albedo feedbacks are also apparent in the warming at high latitudes, indicating that the cooling effect of geoengineering at these latitudes (Fig. 3a) has by this time been overwhelmed by the warming due to GHGs.

3.3 Precipitation

The mean change in June–August precipitation rate is shown in Fig. 3d and e for HadGEM2 and ModelE, respectively. While the distributions clearly differ in some areas (e.g. ModelE shows a reduction of precipitation in the eastern USA, whereas HadGEM2 suggests an increase), nevertheless the results from both models again share certain broad features. Tropical precipitation maxima over the Atlantic and much of the Pacific oceans are displaced southwards in both models, resulting in precipitation reductions in sub-Saharan Africa and the land areas around the Bay of Bengal. This is in response to the hemispheric asymmetry in the temperature change (Fig. 3a), such that the precipitation maximum associated with the inter-tropical convergence

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zone (ITCZ) moves southwards towards the warmer hemisphere (e.g., Williams et al., 2001; Rotstayn and Lohmann, 2002).

It must be remembered that the changes in precipitation described above are with respect to the corresponding period (years 11–20) of the A1B simulations, not with respect to approximately current conditions. Further, the geoengineering simulations during this period are considerably cooler than current conditions due to the idealised manner in which SO_2 injection is applied. The change in mean June–August precipitation in HadGEM2 between the 1990–1999 mean and the years 29–38, the decade when global-mean temperature is about the same as the 1990–1999 period, is shown in Fig. 3f. As well as a reduction in global-mean precipitation, consistent with the results of Bala et al. (2008) and Robock et al. (2008), the increases in GHG concentrations have also caused significant changes in regional precipitation, despite the fact that employing geoengineering has meant virtually no change in global-mean temperature. The precipitation maximum associated with the ITCZ has generally moved northwards in response to the asymmetric warming due to GHGs, and although geoengineering has somewhat ameliorated this change (as indicated by Fig. 3d), the changes induced by increasing GHG concentrations clearly dominate.

4 Discussion and conclusions

We have compared the impact of geoengineering by stratospheric SO_2 injection in two fully coupled climate models, HadGEM2 and ModelE. While there are numerous differences in detail (including the forcing induced by SO_2 injection), there is also considerable agreement between the two models. Both suggest a reduction in near-surface air temperature which is global in extent and distributed in a similar fashion to the warming caused by GHGs (e.g. Fig. 6a in Jones et al., 2009). Both models also indicate that this form of geoengineering causes a southward displacement of the tropical precipitation maximum. This may counteract to some degree the northward shift caused by increases in GHG concentrations, but the latter still dominate.

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The HadGEM2 simulations suggest that the SO_2 injection rates considered here could defer a given amount of global-mean warming under the A1B scenario by 30–35 years. However, both models also indicate a rapid warming if geoengineering is not maintained, which raises serious issues when considering the amount of time over which geoengineering would need to be sustained.

The patterns of temperature and precipitation responses to geoengineering via stratospheric SO_2 injection differ from those via modification of marine stratocumulus cloud sheets in HadGEM2 (Jones et al., 2009). The stratospheric SO_2 injection geoengineering simulations produce geographic responses which, being more homogeneous, more closely counteract the responses due to increasing concentrations of GHGs than do the responses from stratocumulus modification.

The results from HadGEM2 suggest that increases in GHG concentrations can still have a profound impact on regional climate even if geoengineering is successful in counteracting any change in global-mean temperature. Maintaining global-mean temperature near its current level might be considered a necessary goal for any geoengineering proposals, but it is by no means sufficient. It should also be borne in mind that, in common with other geoengineering proposals to modify the Earth's radiation balance, stratospheric SO_2 injection does nothing to offset other impacts of increasing GHG concentrations, such as ocean acidification.

The similarity of the temperature and precipitation responses in the two models hardly constitutes a consensus on the impacts of geoengineering via stratospheric SO_2 injection across the scientific community. It is therefore important for many different climate models to assess the impact of such geoengineering, ideally using a common experimental design, before any consideration is given to practical implementation of such proposals.

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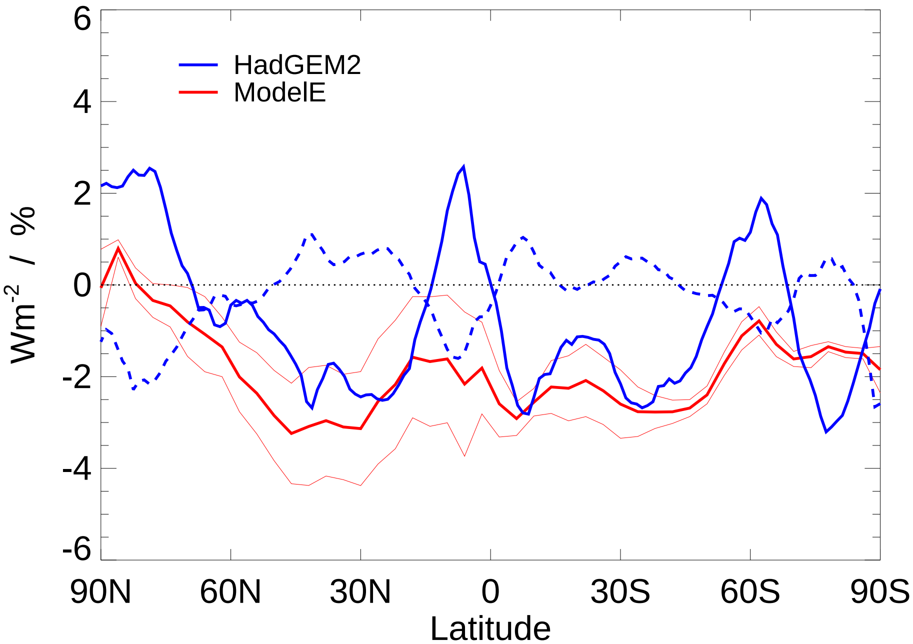

Fig. 1. Annual zonal-mean change in incident surface shortwave radiation (Wm^{-2}) due to geoengineering by SO_2 injection into the lower stratosphere averaged over the second decade in HadGEM2 (solid blue line) and ModelE (thick red line). The thin red lines indicate ±one standard deviation of the difference between the decadal means of the ModelE ensembles. The dashed blue line indicates the change in total cloud cover (%) in HadGEM2.

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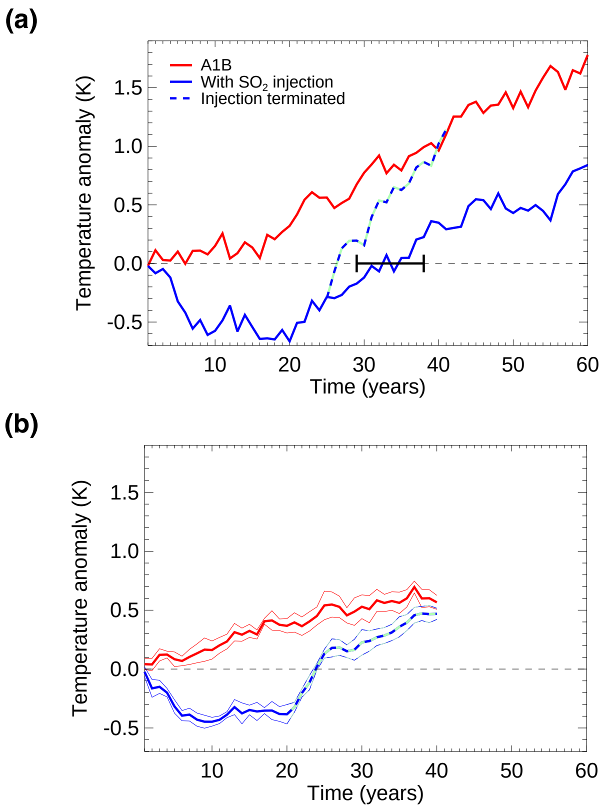

Fig. 2. **(a)** Evolution of annual global-mean near-surface air temperature anomaly (K) in HadGEM2 with respect to the 1990–1999 mean in a historical simulation. The red line is for the A1B scenario, solid blue line A1B plus geoengineering, and dashed blue line after geoengineering has been terminated. The 10-year period over which the mean near-surface air temperature anomaly is zero is marked. **(b)** As (a) but for ModelE, with the anomaly being with respect to the constant-1999 control. The thin lines indicate ±one standard deviation of the difference between the annual means of the ModelE ensemble members.

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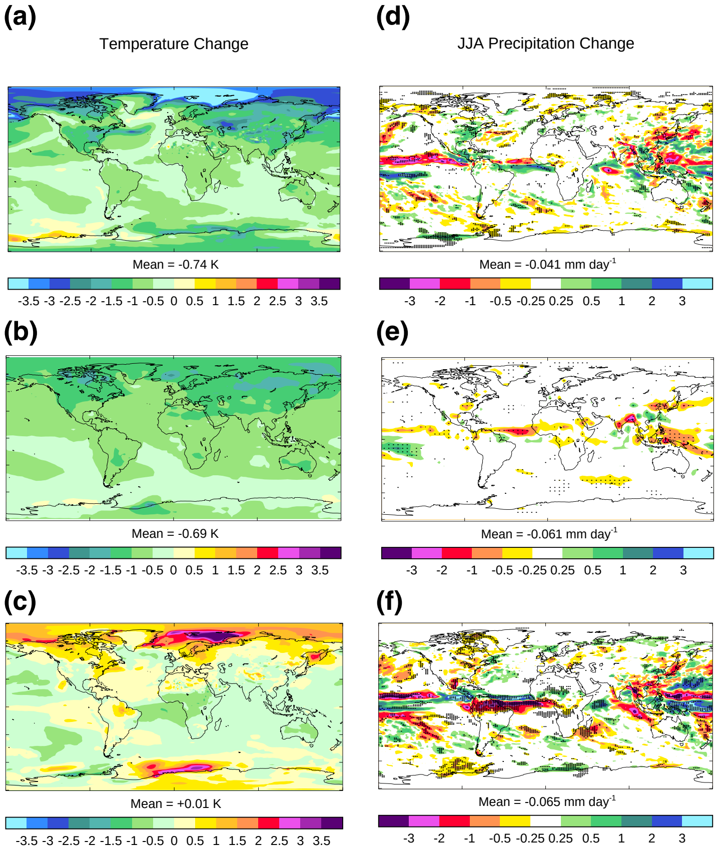

Fig. 3. **(a)** Difference in annual-mean near-surface air temperature (K) between the A1B-plus-geoengineering and A1B simulations in HadGEM2, meaned over the second decade of simulation. **(b)** As (a) but for ModelE. **(c)** As (a) but comparing years 29–38 of the A1B-plus-geoengineering simulation with the 1990–1999 period in a historical simulation. **(d)** As (a) but for change in mean June-August precipitation rate (mm day^{-1}) in HadGEM2; areas where changes are significant at the 5% level are indicated by dots. **(e)** As (d) but for ModelE. **(f)** As (c) but for change in mean June–August precipitation rate.