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Cite this article: MacMartin DG, Caldeira K, Keith DW. 2014 Solar geoengineering to limit the rate of temperature change. *Phil. Trans. R. Soc. A* **372**: 20140134.
<http://dx.doi.org/10.1098/rsta.2014.0134>

One contribution of 15 to a Theme Issue ‘Climate engineering: exploring nuances and consequences of deliberately altering the Earth’s energy budget’.

Subject Areas:

climatology

Keywords:

geoengineering, climate change, feedback

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Electronic supplementary material is available at <http://dx.doi.org/10.1098/rsta.2014.0134> or via <http://rsta.royalsocietypublishing.org>.

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Solar geoengineering has been suggested as a tool that might reduce damage from anthropogenic climate change. Analysis often assumes that geoengineering would be used to maintain a constant global mean temperature. Under this scenario, geoengineering would be required either indefinitely (on societal time scales) or until atmospheric CO₂ concentrations were sufficiently reduced. Impacts of climate change, however, are related to the rate of change as well as its magnitude. We thus describe an alternative scenario in which solar geoengineering is used only to constrain the rate of change of global mean temperature; this leads to a finite deployment period for any emissions pathway that stabilizes global mean temperature. The length of deployment and amount of geoengineering required depends on the emissions pathway and allowable rate of change, e.g. in our simulations, reducing the maximum approximately 0.3°C per decade rate of change in an RCP 4.5 pathway to 0.1°C per decade would require geoengineering for 160 years; under RCP 6.0, the required time nearly doubles. We demonstrate that feedback control can limit rates of change in a climate model. Finally, we note that a decision to terminate use of solar geoengineering does not automatically imply rapid temperature increases: feedback could be used to limit rates of change in a gradual phase-out.

1. Introduction

Much of the discussion on solar radiation management (SRM; variously sunlight reflection methods) either implicitly or explicitly assumes that it would be used to maintain an approximately constant global mean temperature, e.g. restoring to pre-industrial, or avoiding temperature rising above some threshold. This includes almost all SRM simulations to date, including early work [1] and both steady-state and transient experiments G1–G3 in the current GeoMIP simulations [2,3]; some recent papers have been even more explicit, using feedback to maintain a particular temperature [4,5].

This implied framing in existing analyses could have a significant effect on perceptions of SRM risks as it implies that, once deployed, there is a necessity to maintain an SRM deployment either for millennia or until CO₂ concentrations were sufficiently reduced; this raises legitimate concern over the possibility that, at some point during that time interval, the deployment might be interrupted, leading to rapid warming [6–13].

Temporary SRM deployment solely to limit rates of temperature change would avoid millennial-scale implementation, and while it would not address problems such as temperature-dependent tipping point thresholds, it could reduce impacts and risks that are associated with rates of change [14,15]. Recent and projected rates of change are significantly higher than historical levels, creating challenges for ecosystem adaptation [16,17]. In addition to ecosystem responses, some physical climate thresholds may also be rate dependent [18]. Rates of change are also an important factor in human impacts from climate change [11,19]. At a minimum, introducing a delay in reaching any particular temperature-dependent climate impact would increase the amount of time to both learn and adapt; by reducing the needed rate for adaptation, it could reduce economic costs of adaptation, although the societal response to delaying impacts is unclear. An *ad hoc* temporary SRM approach was suggested by Wigley [6], and Eliseev *et al.* [20] arrive at a temporary solution by allowing some rate of change, similar to the approach described here. More recently, Keith [14] and Keith & MacMartin [15] have explicitly described a geoengineering scenario that would be temporary, by cutting the rate of radiative forcing growth in half. Keith & MacMartin [15] also motivate using SRM only to partially offset the anthropogenic radiative forcing from other sources, because the risks associated with using solar geoengineering increase with higher solar reductions. Offsetting all other anthropogenic radiative forcing would also overcompensate precipitation changes [21].

Scaling the radiative forcing growth rate still leads to uncertainty in the rate of climate change owing to uncertainty in the climate response. Rather than cutting the radiative forcing growth rate, here we use feedback of the global mean temperature to limit the rate of change of temperature directly. We consider the different representative concentration pathways (RCPs) [22,23] that are frequently used as standard scenarios to explore future anthropogenic climate change [24], and explore how the choice of emissions pathway and the value chosen for the maximum allowable rate of temperature change affect both the duration and the amount of SRM deployment. The decision to use SRM could influence the emissions pathway; results here for any particular RCP should thus be interpreted as applying to the pathway followed in conjunction with SRM, and, as in any SRM simulation, cautiously interpreted in comparing with the same pathway without SRM.

We use feedback [4,5] of ‘observations’ (here, model output) to adjust the level of SRM in order to achieve a specified rate of temperature change in our simulations. If some forms of SRM were ever implemented, models of the climate system would presumably be used to estimate how much radiative forcing would be needed to meet the desired objectives. However, because the models would never exactly match the real world, feedback would be needed to adjust the radiative forcing of SRM based on the observed climate. Even if not explicitly planned, a prolonged period of warmer or cooler than expected temperatures could lead to an adjustment of the amount of solar geoengineering applied—this adjustment in response to observations (or changing circumstances) is a feedback process; a form of adaptive ecosystem management [25] here applied at planetary scale. Feedback is thus an essential tool for managing uncertainty.

Furthermore, once this feedback of observations is included, it is no longer necessary to have an accurate model of the climate system in order to meet specified climate objectives [5]; the model needs only to be good enough to design the feedback strategy, and make an initial rough estimate for how much to adjust solar reductions in the next year based on the change in anthropogenic radiative forcing from the previous year; this initial adjustment will then be corrected based on observation-based feedback. Of course, any observational errors [26] will result in the feedback tracking observational estimates rather than the actual climate state.

Following prior work [1], we represent solar geoengineering generically as a reduction in solar insolation at the top of the atmosphere. We use the HadCM3L fully coupled atmosphere–ocean general circulation model (GCM) as our representation of the unknown ‘real world’, and a much simpler box-diffusion model as our approximate model. These are described in more detail in §3, but a key insight is that this simple model is sufficient when using feedback. We also use this simple model for computationally efficient predictions of the transient global mean temperature response in parametric explorations.

We estimate the amount of solar insolation reduction required to achieve a target rate of warming using the box-diffusion model. In our GCM simulations, we adjust this estimate each year based on feedback of the global mean temperature to maintain a roughly constant rate of temperature increase; this feedback compensates for any differences between the simple model and the GCM. This approach—combining prediction and correction—thus captures the situation that would be faced in actual implementation, where we do not have the option to re-run a simulation in order to tune the amount of SRM.

2. Impact of representative concentration pathway and allowable rate of change

The temperature and its rate of change for different RCPs is shown in figure 1, calculated using the box-diffusion model that has been tuned to match the HadCM3L AOGCM response. A climate sensitivity higher or lower than the HadCM3L value of 3.2°C per CO_2 -doubling would scale both the temperature and its rate of change. The rates of change are calculated from a running 30 year linear least-squares fit, and expressed as a decadal rate of change. The peak rate of change over any 30 year period is roughly 0.25, 0.3, 0.35 and 0.55°C per decade for RCP 2.6, 4.5, 6.0 and 8.5 pathways, respectively.

First, consider the specific example of using SRM to constrain the maximum rate of change to 0.1°C per decade or 1°C per century; this is roughly half the century-scale warming rate for RCP 4.5 in this model. HadCM3L simulation results are shown in figure 2 for an RCP 4.5 emissions pathway. Temperatures for remaining pathways are shown in the electronic supplementary material, figure S1; the required solar reduction for each pathway is shown in figure 3. Note that the use of feedback results in insolation reductions that unavoidably respond to natural variability [4], but ensures that the target trajectory of 0.1°C per decade is approximately followed.

While the rate of change of global mean temperature in the simulations in figure 2 is constrained to the specified level, the rate of change is not spatially uniform; this is shown in figure 4; see the electronic supplementary material, figure S2, for a discussion of the statistical significance of local rates of change. If solar geoengineering is used to limit the rate of change of global mean temperature to 0.1°C per decade, the rate of change of temperature is reduced in most places, but not uniformly. Even with a target of a constant global mean temperature, regional temperatures do not remain constant owing to the difference in the response pattern between greenhouse gas forcing and that resulting from solar reductions [27].

We discuss two metrics that can be evaluated to characterize the amount of solar reduction required for any specified rate of change of temperature and for any emissions pathway. First, the duration of SRM deployment; for any of the RCPs, this will be finite for any specified rate of change greater than zero, because all of the RCPs eventually stabilize radiative forcing and thus temperature increase. By contrast, using SRM to maintain a constant global mean temperature

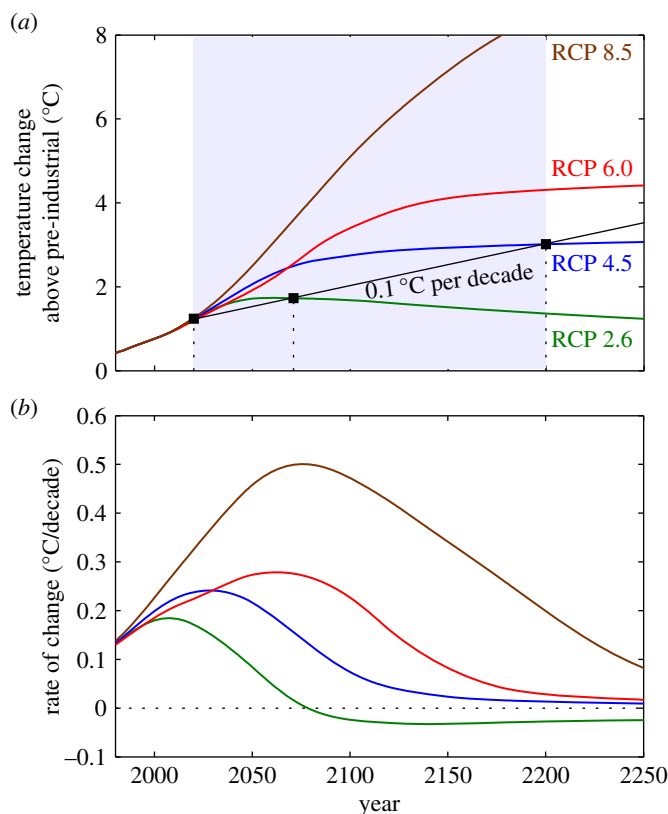


Figure 1. Predicted global mean temperature (a) and rate of change (b) corresponding to different RCPs, computed using a box-diffusion model with a climate sensitivity of 3.2°C per CO_2 -doubling and time constants chosen to match the HadCM3L GCM behaviour. (The results scale linearly with climate sensitivity.) Rates of change are calculated over 30 year intervals, and expressed in degrees Celsius per decade. A 0.1°C per decade rate of change is also shown in (a), starting in 2020, and for RCP 4.5, the approximate time over which SRM would be required in order to maintain this rate is shaded. (Online version in colour.)

results in an SRM deployment that would greatly exceed the simulation time horizons considered here, and for CO_2 emissions scenarios, would last at least until such time that atmospheric greenhouse gases are naturally or artificially removed from the atmosphere. A second metric is the peak solar reduction required at any point during the deployment. This is relevant for understanding risks associated with the amount of solar reduction, such as ozone depletion if stratospheric aerosols are used, although this would also depend on the timing of the peak because it depends on halogen concentrations. A third metric could be the integrated amount of solar reduction over the entire deployment, i.e. the shaded region in figure 2. The average solar reduction over the deployment is roughly half of the maximum value, so this can be estimated from the duration and peak solar reduction (see electronic supplementary material for details).

The amount of solar reduction required to maintain a 0.1°C per decade rate of change for different RCP scenarios is shown in figure 3, for both the box-diffusion model prediction and the HadCM3L simulation; these cases can be used to evaluate the metrics described above. The box-diffusion model provides a good prediction except for the RCP 8.5 case, owing to nonlinearities in the HadCM3L temperature response at high radiative forcing. This case also serves to illustrate the importance of using feedback of the 'observed' temperature to compensate for errors between the prediction model and the actual system. While here the box-diffusion model was tuned to match HadCM3L behaviour, this would not be possible in a real deployment.

The length of time that a solar geoengineering system would need to be deployed and the maximum value of solar reduction required are shown for the box-diffusion model in figure 5.

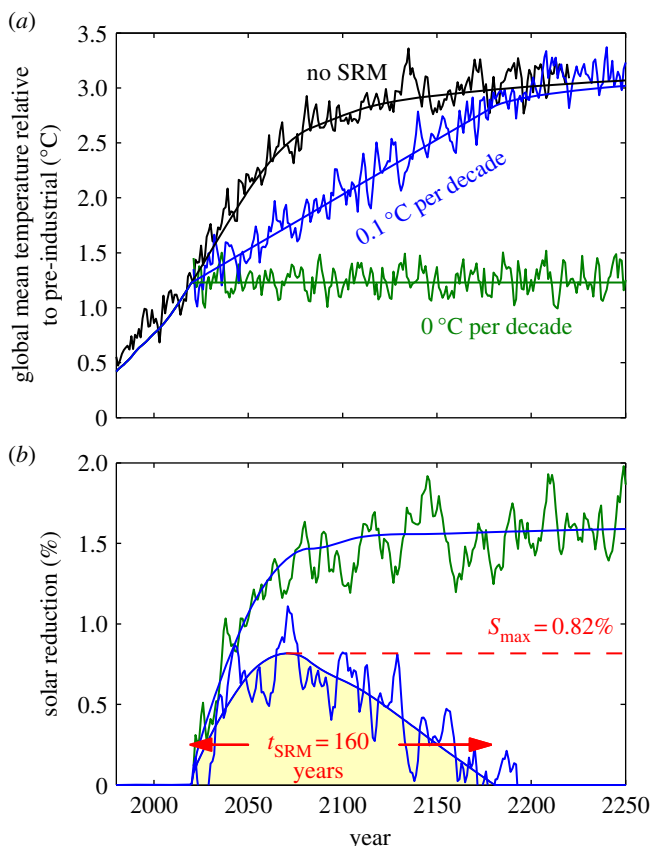


Figure 2. Solar geoengineering used either to maintain constant global mean temperature ('0°C per decade') starting in 2020 or to limit rate of change to 0.1°C per decade for an RCP 4.5 emissions pathway (other RCP cases are shown in the electronic supplementary material). Smooth lines (with no climate variability) are from the box-diffusion model, whereas lines with climate variability are from HadCM3L. For HadCM3L, feedback of the global mean temperature is used to adjust the level of solar reduction to maintain the temperature at its chosen value. Global mean temperatures are shown in (a), and the corresponding solar reduction in (b). Also shown in (b) is the maximum solar reduction (S_{\max}) predicted by the box-diffusion model for the 0.1°C per decade case, the length of time over which SRM would be required to achieve this (t_{SRM}), and the integrated amount of SRM (shaded region); these metrics are shown in figure 5 and the electronic supplementary material, figure S3, for different RCPs and allowable rates of change. (Online version in colour.)

The integrated solar reduction over the deployment is shown in the electronic supplementary material, figure S3 and table S1. The choice of emissions trajectory has a profound influence over the magnitude and duration of geoengineering required to limit the rate of change of global mean temperature. For the 0.1°C per decade case illustrated in figures 2 and 3, the time required increases from roughly 40 years with RCP 2.6 to more than 800 years for RCP 8.5, whereas the maximum solar reduction increases from 0.25% to roughly 5%. Figure 5 is calculated using the box-diffusion model; the values estimated for RCP 8.5 are thus slightly too high owing to the nonlinearity noted above.

The duration and maximum amount of solar reduction presented herein are strongly dependent on the assumed climate sensitivity, shown in figure 6, giving some insights into the uncertainty in these metrics.

The use of feedback to maintain a specified rate of change of temperature is also relevant if a choice was made to terminate geoengineering. It has often been stated that terminating a solar

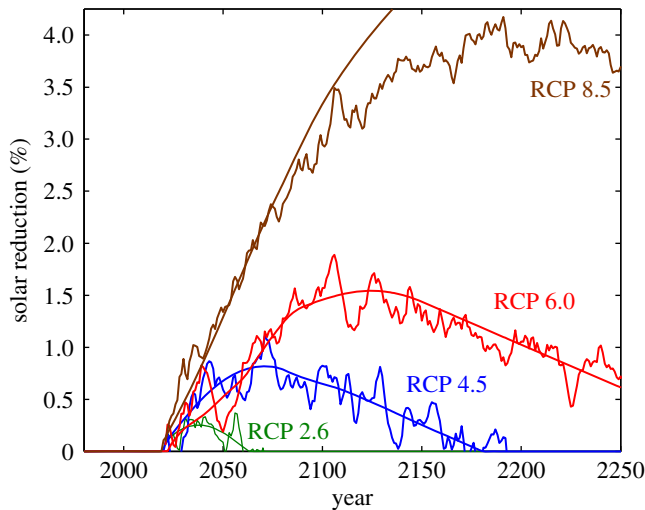


Figure 3. Comparison of the solar reductions required to maintain a 0.1°C per decade rate of temperature change for different RCP emission pathways. The RCP 4.5 case is the same as in figure 2b. Each case is predicted using the box-diffusion model, and then simulated using HadCM3L, with feedback to correct for differences between the box-diffusion model and the GCM. Note that the box-diffusion model in this case provides a good estimate for RCP 2.6, RCP 4.5 and RCP 6.0, but that nonlinearities in HadCM3L at high radiative forcing result in the box-diffusion model giving a poorer prediction for RCP 8.5: this illustrates the value of using feedback, as the 0.1°C per decade rate of change of temperature is maintained (see electronic supplementary material, figure S1) despite the model errors. (Online version in colour.)

geoengineering deployment would lead to rapid temperature change; for example, the recent Intergovernmental Panel on Climate Change report [28] includes the statement ‘If SRM were terminated for any reason, there is high confidence that global surface temperatures would rise very rapidly...’. While this is clearly true if some war or calamity caused a *sudden* termination in the use of solar geoengineering, it is important to note that this does not follow if there was a conscious choice to phase-out solar geoengineering for some reason, such as newly discovered side-effects. Furthermore, if a sudden termination did occur, it is conceivable that the solar geoengineering deployment might be rapidly re-initiated. Such a brief termination might have characteristics of a similar magnitude but opposite in sign to those of a volcanic eruption. The approach used here is also applicable to limit how rapidly the climate is allowed to warm, trading off impacts from the newly discovered side-effects against the impacts from rapid warming. An example is shown in figure 7; clearly, any warming rate can be imposed, with consequences on how much longer some level of SRM would still be required.

3. Methods

Simulations herein use the HadCM3L fully coupled atmosphere–ocean general circulation model [29], forced by different RCPs [22,23]. HadCM3L has a climate sensitivity of approximately 3.2°C , similar to the 3.4°C average of the more current CMIP5 models [30]; it is thus well suited to give a reasonable mid-range estimate of global mean-temperature response. The transient response of the global mean temperature in HadCM3L is quite well captured by either a semi-infinite diffusion model [31] or a box-diffusion model [4]; this is also consistent with the dynamic behaviour of most of the CMIP5 models [32].

The box-diffusion model relates perturbations in surface temperature $T(t)$ in response to radiative forcing perturbation $F(t)$ via

$$C \frac{dT}{dt} = F - \lambda T + \beta \left. \frac{\partial T_d}{\partial z} \right|_{z=0} \quad (3.1)$$

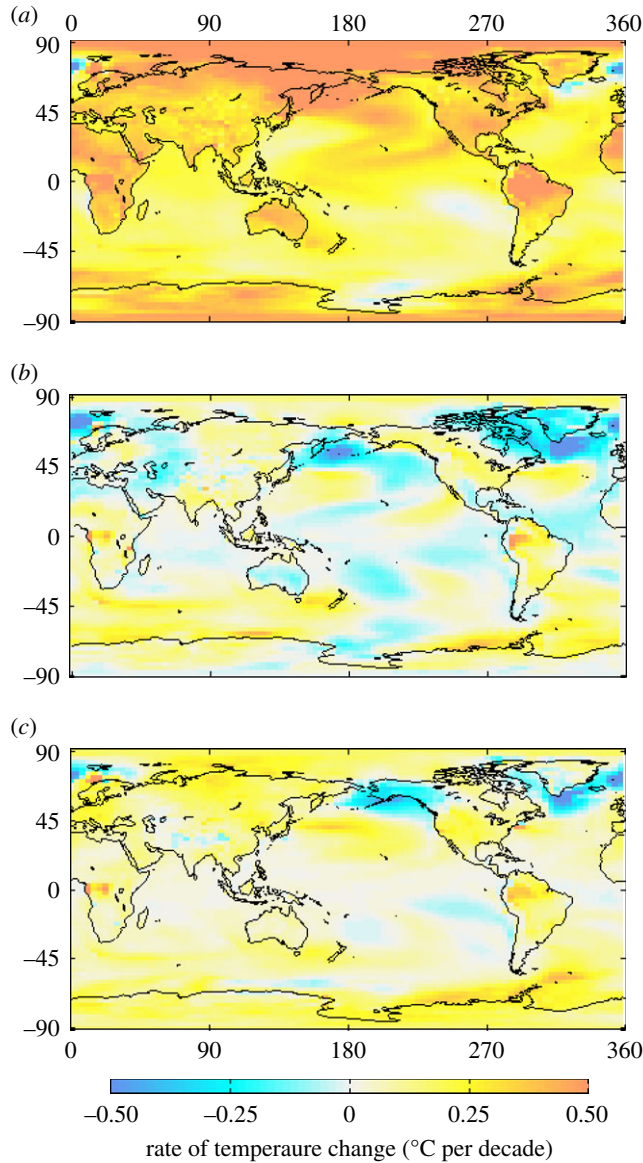


Figure 4. Rate of temperature change at grid-scale in HadCM3L for RCP 4.5 over a 30 year period from 2020 to 2050 without solar geoengineering (a) and with solar geoengineering either to maintain constant global mean temperature (b) or to limit global mean temperature warming to 0.1°C per decade (c). Slopes are estimated using a linear least-squares fit and averaged over five ensemble members. The local rate of change of temperature can still be much larger than the global mean rate, but for the 0.1°C per decade case, is reduced in most places with SRM when compared with no SRM. Using SRM to maintain a constant global mean temperature despite increasing greenhouse gas concentrations results in some regions warming and some cooling, so that the average rate of change is zero. The grid-scale rate of change is not statistically significant everywhere (see electronic supplemental material, figure S2). (Online version in colour.)

and

$$\frac{\partial T_d}{\partial t} = \kappa \frac{\partial^2 T_d}{\partial z^2}, \quad (3.2)$$

with deep ocean temperature $T_d(z, t)$ and boundary condition $T_d(0, t) = T(0, t)$ (taking the top of the deep ocean as $z = 0$). Closed-form solutions for $T(t)$ can be obtained from Laplace transforms

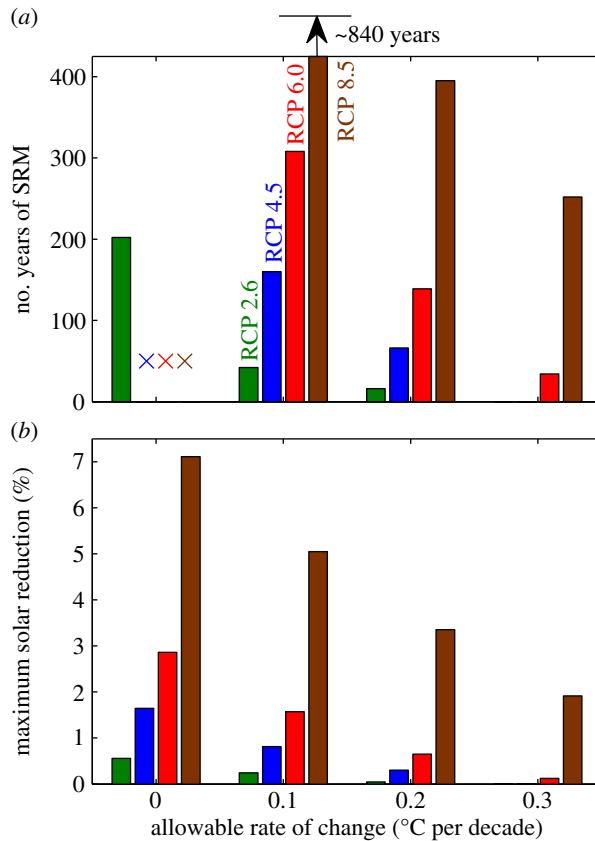


Figure 5. The duration (a) and peak amount (b) of solar geoengineering that would be required to constrain the rate of change of temperature, for different RCP emission pathways. Values for these metrics are significantly larger for RCP 8.5 than for other pathways; the arrow indicates a value above the plotted range. If the SRM is used to maintain a constant temperature (zero rate of change), the maximum solar reduction is finite for each RCP, but the duration is only finite for RCP 2.6 (indicated by '×' for other RCPs). Results are calculated using a box-diffusion model tuned to match HadCM3L behaviour. Values also given in the electronic supplementary material, table S1. (Online version in colour.)

as in [4]; it is straightforward given this 'forward' solution to compute the 'inverse' solution of finding a forcing trajectory over time $F(t)$ that yields any desired temperature trajectory $T(t)$. The parameter λ describes the natural climate feedback (the change in radiation due to a change in surface temperature), $C = c\rho H$ is the surface layer heat capacity per unit area, κ is the thermal diffusivity and $\beta = c\rho\kappa$ for density ρ and specific heat capacity c . The time constants of this model can be obtained from a fit to the frequency-dependent response of HadCM3L as in MacMartin *et al.* [4]; this frequency response was previously calculated by simulating the response to sinusoidal variations in the solar 'constant' at different frequencies [31]. These simulations give the HadCM3L response to solar forcing; to account for the difference in efficacy of solar forcing relative to CO_2 , the result is scaled to match the HadCM3L response to RCPs.

This box-diffusion model is used here for two purposes. First, for calculating the length of time and the amount of solar reduction required for a given RCP emissions pathway and allowable rate of change in figures 5 and 6; the resulting estimates are reasonable proxies for the response of the HadCM3L GCM but more efficient to calculate. Note that computing the solar reduction that yields temperatures $T(t)$ requires a dynamic inverse model, such as the box-diffusion model used here. Second, this simple model is also used for providing an initial estimate for HadCM3L simulations of the solar reductions required; these are subsequently corrected using feedback.

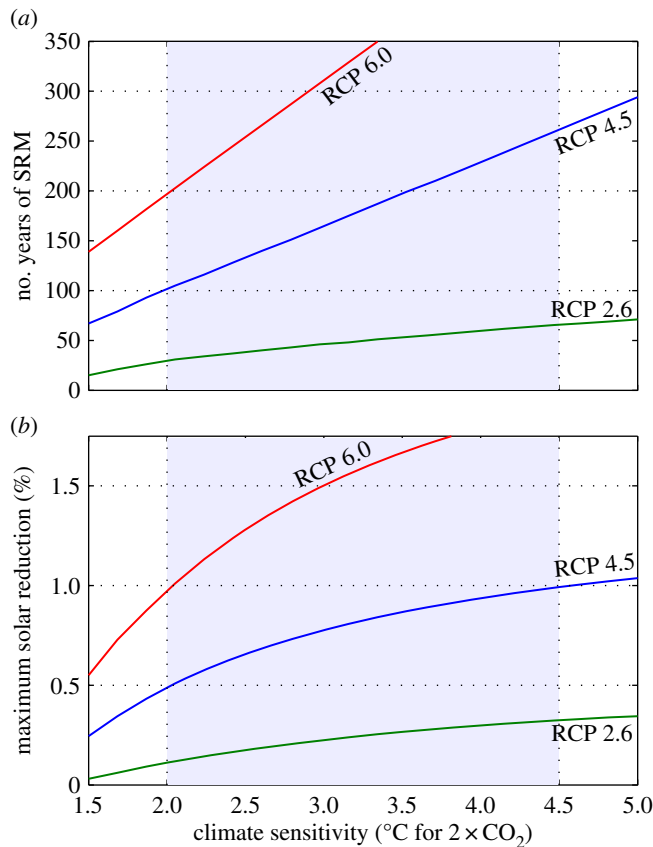


Figure 6. Dependence on climate sensitivity for using solar geoengineering to limit the rate of change of global mean temperature to 0.1°C per decade showing number of years that would be required (a) and maximum solar reduction required (b). Results for RCP 8.5 are off the scale for all climate sensitivities shown here. The ‘likely’ range of climate sensitivity of $2\text{--}4.5^{\circ}\text{C}$ per doubling of CO_2 [24] is shaded; HadCM3L sensitivity used in other figures is 3.2°C for a doubling of CO_2 , roughly in the middle of this range. (Online version in colour.)

As noted earlier, because feedback is being used, only a very simple model is needed for this purpose; the estimated solar reduction would not be more accurate if one or more GCMs were instead used for this purpose. Indeed, our simple model is tuned to reproduce the GCM response more accurately than might be possible in a real implementation. (This depends on how good climate models become in the future.)

With the well-tuned box-diffusion model, then, in our simulations, feedback would only be required to correct for nonlinearity in the RCP8.5 simulation. However, we use feedback in all HadCM3L simulations regardless, in order to better represent the situation that would be faced in a real implementation. Once feedback is used, the resulting behaviour is relatively insensitive to significant model error [5], and so choosing a more accurate prediction model does not affect our HadCM3L simulations (i.e. a less accurate prediction model would lead to similar behaviour as the errors would be corrected through the use of feedback). We choose to accurately tune the box-diffusion model here, so that the same model can be used as an efficient proxy for the full HadCM3L simulation in the parametric calculations.

We use reduction in solar intensity as a proxy for any SRM method. In HadCM3L simulations with SRM, we adjust the reduction in solar intensity using feedback of the ‘observed’ (i.e. simulated by HadCM3L) global mean temperature in order to track the specified target temperature as a function of time, despite model uncertainty. We use a proportional–integral (PI)

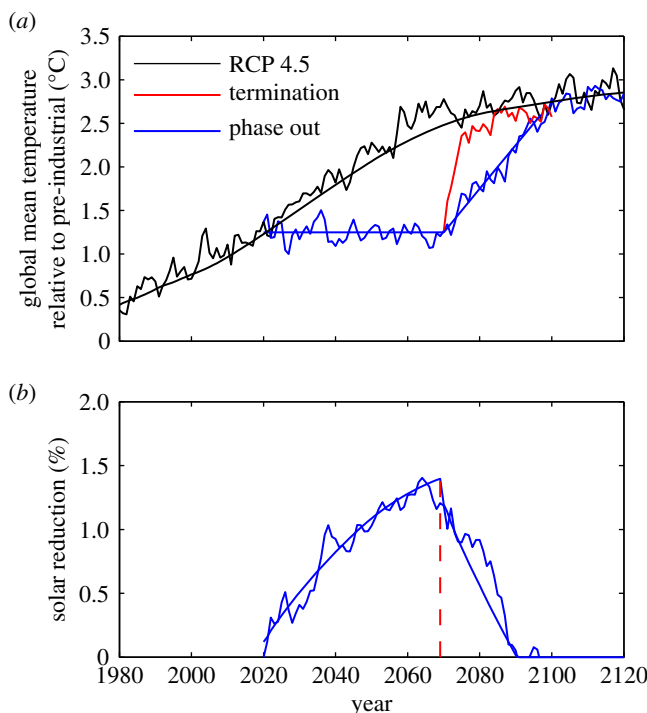


Figure 7. Illustration of gradual phase-out of a solar geoengineering deployment, in contrast with a sudden termination. The gradual phase-out uses feedback to limit warming to 0.5°C per decade. (a) The simulated global mean temperature response in HadCM3L and (b) the corresponding solar reduction as in figure 2. The feedback case initiates SRM in 2020 with the goal of maintaining global mean temperature constant at 2020 levels, and is either suddenly terminated or gradually phased out after 50 years (2070), when the temperature difference relative to the case without SRM is roughly 1.5°C . The sudden termination results in a rapid warming of more than 1°C in the first 5 years; the gradual phase-out example shown here spreads the overall warming out over 25 years. (Online version in colour.)

controller [4] to compensate for errors in the estimated solar reduction versus time. The solar reduction S_{k+1} to apply in year $k + 1$ is calculated from the ‘observed’ temperature T_k in year k as

$$S_{k+1} = S_{k+1}^* + K_p(T_k - T_k^*) + K_I \sum_{n=0}^k (T_n - T_n^*), \quad (3.3)$$

where S_k^* is the predicted value estimated from the box-diffusion model and T_k^* is the ‘target’ temperature in year k corresponding to the specified maximum rate of change. We chose integral and proportional gains of $K_p = 0.5$ and $K_I = 0.25$ in units of % solar per $^{\circ}\text{C}$; these values give a time-constant of about 5 years for the feedback to respond to an error [4]. Note that a consequence of using feedback is that the applied solar reduction is ‘noisy’. The response to natural variability is an unavoidable result of using feedback to adjust forcing. The feedback gains can be chosen to trade off this response to natural variability against the accuracy of tracking the chosen reference trajectory: higher gains increase accuracy at the expense of volatility; we make no claim that the gain values used here are the best choice for this trade.

Reference or target trajectories for the global mean temperature are defined here starting in 2020 (arbitrarily chosen) and increasing at a constant rate. Of course, this approach could be used to follow any temperature profile. The box-diffusion curves in figures 2, 3 and 7 compute the radiative forcing required to obtain this temperature trajectory, constrain the radiative forcing to be negative or zero, and compute the resulting feasible temperature trajectory for the system. Note that the resulting predicted length of SRM deployment is slightly shorter than the shaded

region in figure 1 owing to climate inertia: solar reductions can be tapered off slightly earlier than figure 1 would suggest as the climate warms at less than the specified rate once the temperature is sufficiently close to the value it would have been if there was no solar reduction.

4. Discussion

Carbon dioxide released to the atmosphere can affect the Earth's climate for millennia [33], thus in the absence of methods used to accelerate the removal of CO₂ from the atmosphere, CO₂ emissions commit us to millennia of altered climate. Using solar geoengineering to hold global mean temperature constant would thus require that its deployment be sustained for a long time, dependent on this residence time. (The residence time of aerosols in the stratosphere is only a year or 2 [34]; the millennial-scale commitment is associated with carbon dioxide, not stratospheric aerosols or other means to reduce solar forcing.)

However, solar geoengineering technologies could instead be used only to limit the rate of change of global mean temperature to some chosen maximum value. This would only require a temporary solar geoengineering deployment, yet would still reduce those impacts of climate change which are rate dependent. In particular, using SRM to limit the rate of temperature change would provide more time for both ecosystems and human systems to adapt to climate changes. Any temperature-dependent impacts would of course only be delayed, not avoided, and the resulting impact of this delay on CO₂ emissions mitigation is unclear.

Increasing the maximum allowable rate of change reduces both the length of time and the amount of solar geoengineering that would be required to maintain this rate. Reducing the amount of solar reduction in a deployment would reduce risks associated with the technology used (e.g. ozone depletion)—and less solar reduction is required if using solar geoengineering only to limit the rate of change rather than to hold the global mean temperature approximately constant. In an ideal world, the rate of change might, in principle, be chosen to balance undesired impacts from the solar geoengineering deployment against the damages associated with a changing climate. While the use of solar geoengineering to reduce only rates and not amounts of climate change greatly reduces the duration of the required deployment, the time horizons are still long in comparison with most policy commitments. Figure 5 makes it clear that the emissions pathway that is followed has a substantial impact on both how much and how long solar geoengineering would need to be deployed in order to limit the rate of change of temperature to some given value.

The motivation to deploy solar geoengineering would presumably be to reduce environmental risk. However, it could be the case that it is not successful at reducing environmental risk, and thus there would be a motivation to terminate the deployment—but a sudden termination might be riskier than continued deployment. We have also shown here that, were this situation to occur, the range of choices would not be confined to the binary choice of terminate or continue deployment, but that there is the possibility of choosing to phase out a deployment at whatever rate might best reduce overall risk and damage.

In this work, we have used a highly schematic climate model to estimate the change in amount of geoengineering that would be needed to attain a target rate of temperature increase in a more complicated three-dimensional climate model, with the amount of geoengineering then further adjusted using feedback. The implication is that the relationship between the schematic model and the full three-dimensional climate model is analogous to the relationship between modern three-dimensional Earth system models and the real Earth in this important respect: in each case, the model used is a simpler and imperfect representation of the more complex system. Our study shows that the model used to estimate required change need not be highly sophisticated or very accurate to achieve a high level of control, because model errors are in large part compensated for by the feedback process. Better models might permit better control, but a high degree of control does not depend on having a model with a high degree of fidelity to the real world.

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