The long-term policy context for solar radiation management

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Abstract We examine the potential role of "solar radiation management" or "sunlight reduction methods" (SRM) in limiting future climate change, focusing on the interplay between SRM deployment and mitigation in the context of uncertainty in climate response. We use a straightforward scenario analysis to show that the policy and physical context determine the potential need, amount, and timing of SRM. SRM techniques, along with a substantial emission reduction policy, would be needed to meet stated policy goals, such as limiting climate change to 2 °C above pre-industrial levels, if the climate sensitivity is high. The SRM levels examined by current modeling studies are much higher than the levels required under an assumption of a consistent long-term policy. We introduce a degree-year metric, which quantifies the magnitude of SRM that would be needed to keep global temperatures under a given threshold.

Given the magnitude of projected climate changes (Meehl et al. 2007), it is unlikely that a warming of 2 °C above pre-industrial levels, a goal of the recent Cancun Agreements (http://cancun.unfccc.int/), could be avoided without abatement action. Solar radiation management or sunlight reduction methods (SRM) are gaining attention as potential additions to the menu of responses in addition to mitigation and adaptation. SRM encompasses a range of potential techniques to reduce the net amount of solar heating of the planet, including stratospheric aerosol injection and ocean cloud enhancement (Rasch et al. 2008; The Royal Society

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2009; Vaughan & Lenton 2011). None of these techniques are understood well enough at present for application, and their potential use raises numerous ethical, technological, scientific, and policy issues that will need to be addressed (The Royal Society 2009; Barrett 2008; Robock 2008).

As noted by others, SRM seems viable only if used in conjunction with emission reductions (Wigley 2006; Goes et al. 2011). This is because SRM alone will not substantially reduce impacts due to ocean acidification, SRM itself will cause ancillary climate changes, and use of SRM without emission mitigation would risk large climate changes if SRM were suddenly stopped (Boucher et al 2009; Brovkin et al. 2009). While reduction in emissions of some short-lived forcing agents might reduce the near-term rate of climate change (Ramanathan and Xu 2010), forcing will eventually be dominated by CO_2. Only a long-term reduction in the net amount of fossil CO_2 entering the atmosphere can stabilize the climate system (Clarke et al. 2007; NAS 2010), which means that CO_2 emission mitigation must remain a central component of climate policy.

Uncertainty is a central facet of the climate problem, particularly the uncertain response of the climate system to increases in greenhouse gas concentrations, which is commonly expressed as the climate sensitivity. The *likely*[2] range of climate sensitivity is estimated to be 2 to 4.5 °C per CO_2 doubling (Forster et al. 2007), and we consider here discrete values over this range (although higher values cannot be ruled out). Additional uncertainties are also present but the relevant issues can be illustrated by focusing on the climate sensitivity.

1 Methods

We use scenario analysis to examine potential future pathways focusing on long-term climate goals, starting with emissions scenarios from the recent Representative Concentration Pathways (RCP) exercise, which was designed to span the range of potential anthropogenic forcing of climate change over the 21st century (Moss et al. 2010). In contrast to the RCP scenarios, which were each produced by different integrated assessment models, we use here emission scenarios developed by the same integrated assessment model, the Global Change Assessment Model (GCAM). This assures consistent changes between scenarios of fossil CO_2, CO_2 from net deforestation, non-CO_2 greenhouse gas, and other pollutant emissions.

We consider SRM in the context of a set of scenarios that illustrate a range of potential mitigation responses (Fig. 1, Table 1), ranging from no action to reduce greenhouse gas emissions (Ref) to a low peak and decline (PD) scenario (GCAM-PD) representative of the most ambitious mitigation scenarios in the current literature. The GCAM reference, RCP4.5-stab, and GCAM-PD scenarios are described in detail elsewhere (Thomson et al. 2011, Electric Supplementary Material - ESM).

In the RCP4.5-stab forcing stabilization scenario the global energy system undergoes a transformation over the 21st century to one with much lower low carbon emissions. The GCAM-PD scenario would require strong policy actions in the near-term. Global carbon dioxide emissions in the GCAM-PD scenario are declining after 2015 with net negative global emissions by the end of the century (van Vuuren, et al. 2007; Calvin et al. 2009; van Vuuren et al. 2011). Decades of net negative emissions are a common feature of low PD

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[1] The IPCC 4th assessment defines *likely* as a 66 % chance of the true value lying within the stated range. Estimated probability distributions for climate sensitivity (Forster et al. 2007) have long tails, so there is a higher probability of the true value being higher than this range than lower.

Emission Scenarios

a)

Total Radiative Forcing
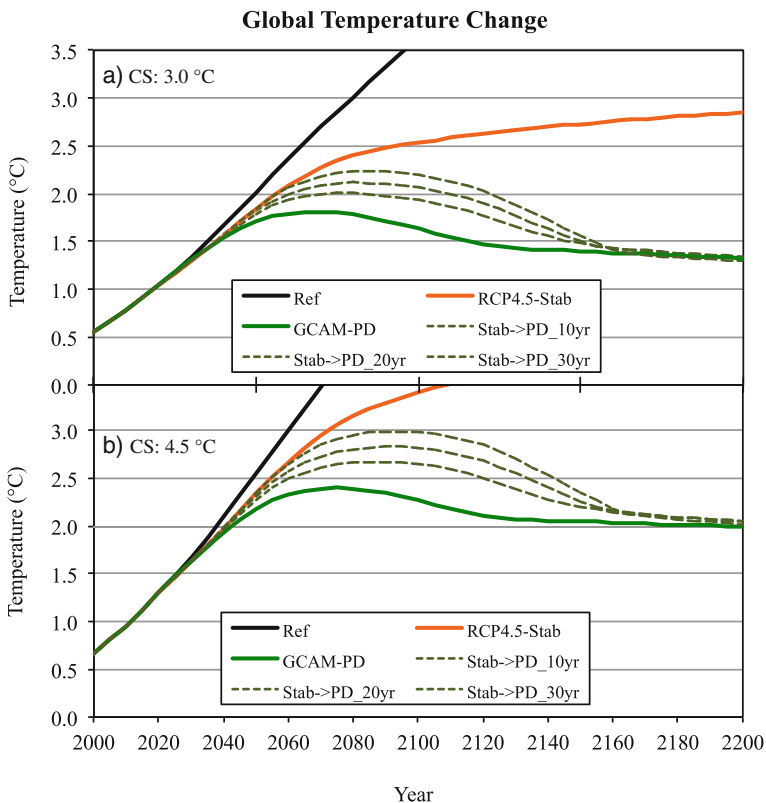*Climate Sensitivity: 3.0 °C/CO$_2$ doubling*

b)
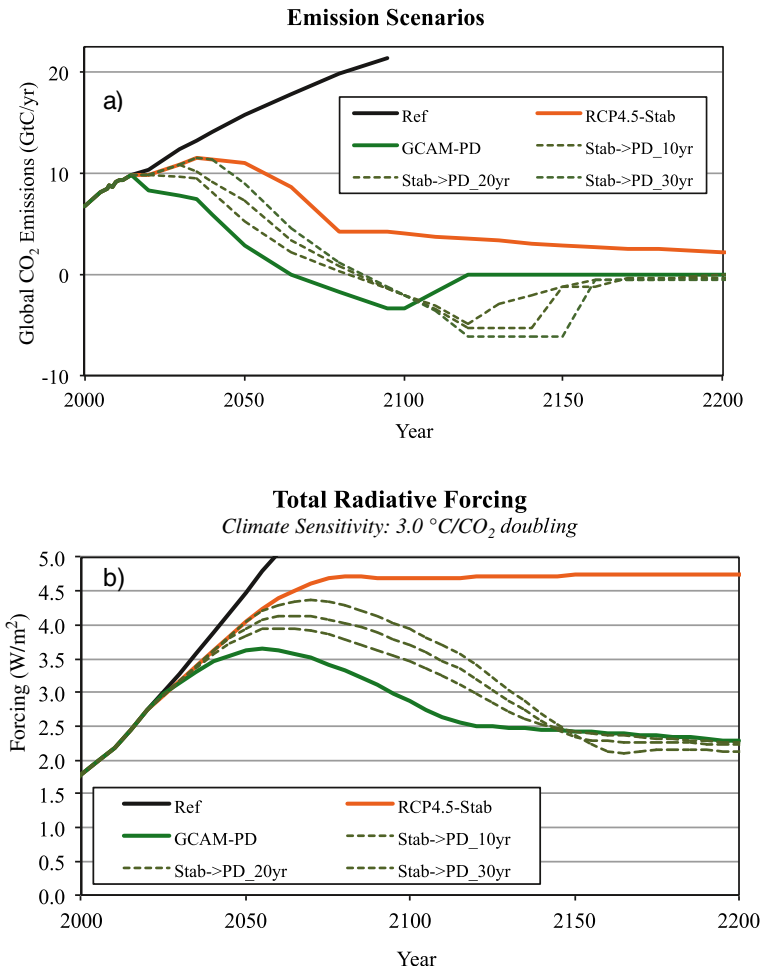
Fig. 1 **a** Global net carbon dioxide emissions from fossil-fuels and cement and **b** total radiative forcing (for a central climate sensitivity of 3.0 °C per CO$_2$ doubling) for a reference case with no climate policy (*black solid line*), stabilization of total anthropogenic forcing at 4.7 W/m^2, (*orange solid line*) and a peak-and decline scenario with total forcing of 2.9 W/m^2 in 2100 with negative emissions into the 22nd century (*green solid line*). Radiative forcing here follows the definition used in the RCP scenarios (see ESM). Dotted lines show scenarios that transition from the stabilization to the PD scenario after (from bottom to top) 10, 20, and 30 years

Table 1 Scenarios used in this analysis

Scenario	Scenario type	2100 CO$_2$ emissions GtC/yr	2150 CO$_2$ emissions GtC/yr	2100 CO$_2$ Conc ppmv	2100 forcing W/m^2
Ref	Reference	21	15	797	6.9
RCP4.5-stab	Stabilization	4.1	2.9	531	4.3
Stab->PD_30yr	Overshoot	−2.0	−6.2	463	3.4
Stab->PD_20yr	Overshoot	−2.0	−1.2	444	3.2
Stab->PD_10yr	Overshoot	−2.0	−1.3	425	3.0
GCAM-PD	Overshoot	−3.4	0.0	380	2.3

scenarios and provide additional flexibility over time as compared to scenarios that do not include this option (Matthews and Caldeira 2008; Vaughan et al. 2009, ESM). Net negative carbon dioxide emissions could be provided by combining biomass electricity generation or biofuel production with carbon dioxide capture and geologic sequestration, through terrestrial policies to enhance forest and soil carbon reservoirs, or through direct carbon dioxide air capture or other carbon dioxide removal techniques (which are often also included under the term geoengineering, Vaughan and Lenton 2011). The low PD scenarios (also called "overshoot scenarios") are fundamentally different as compared to stabilization scenarios in that long-term forcing is smaller than forcing in the interim.

The GCAM-PD scenario may be overly optimistic given that emissions under current commitments will exceed this trajectory (Rogelj et al. 2010; Macintosh 2010). Even if policies are strengthened, the very large changes implied in the GCM-PD scenario, even if feasible, would likely take some time to implement. We therefore also consider three further peak and decline scenarios (dotted lines in Figs. 1 and 2), which represent transitions from the radiative forcing stabilization scenario (RCP4.5-stab) to a peak and decline scenario. The three transition scenarios follow the stabilization scenario for an additional 10, 20, or 30 years (e.g., departing from the RCP4.5-stab emission pathway after 2020, 2030, and 2040) before transitioning to a peak and decline pathway. In general, the *long-term* climate-change commitment can be kept to similar levels if negative CO_2

Fig. 2 Global mean temperature change from pre-industrial levels under the scenarios from Fig. 1 for climate sensitivity (CS) values of **a** 3.0 °C/CO_2 doubling and **b** 4.5 °C/CO_2 doubling

emissions in later years are increased in order to balance the impact of extra emissions in early years (Fig. 1a).

Calculations for radiative forcing, concentrations, and temperature change use the MAGICC 5.3 model, as implemented in GCAM 3.1 integrated assessment model (see ESM). The MAGICC model contains sufficient mechanistic detail to replicate the global temperature response from more complex models (Raper et al. 2001; Smith and Edmonds 2006). The emissions scenarios were constructed using a climate sensitivity of 3.0 °C per CO_2 doubling. The same emissions scenarios were used in all climate sensitivity cases. This means that forcing and stabilization behavior changes with climate sensitivity due to climate and CO_2 feedbacks.

In addition to the climate sensitivity and future emissions pathways, there are also large uncertainties in earth-system dynamics, particularly the carbon-cycle, aerosol forcing, and ocean thermal dynamics. Even assuming a specific value for the climate sensitivity, a substantial uncertainty range will remain. For illustrative purposes, the scenario set-up has been kept as simple as possible. All climate model parameters other than climate sensitivity, for example, have been set to central values. A high climate sensitivity, for example, could be associated with stronger negative aerosol forcing or a larger ocean thermal lag (Meinshausen et al. 2009). A probabilistic analysis could provide additional insights.

2 The context for SRM

Figure 2 illustrates the interaction between policy and uncertainty by showing global mean temperature change for the range of scenarios and two climate sensitivities. Global temperature changes are used as a proxy for the overall magnitude of climate changes, noting that impacts other than average temperature such as changes in precipitation, frequency of extreme events, and the risk of state changes (*e.g.*, ice sheet destabilization or carbon releases from ecosystems) may be the most relevant impacts (Smith et al. 2009). In either a central or high assumption for the climate sensitivity (Fig. 2), global mean temperature change in 2100 under the reference and RCP4.5-stab scenarios are over 2.0 °C and still increasing. This threshold is exceeded by the mid 21st century under a central climate sensitivity and about 15 years earlier if the climate sensitivity is high.

Under a central value for the climate sensitivity of 3.0 °C/CO_2 doubling, any of the PD scenarios used here, ultimately requiring net negative emissions, can meet a long-term 2 °C temperature change goal, although temperatures would exceed this threshold during the 21st century in some cases.

The situation is very different if the climate sensitivity is high. If the climate sensitivity is 4.5 °C/CO_2 doubling (Fig. 2b), global temperatures increases significantly above 2 °C until at least the mid 22nd century. Global mean temperatures under the lowest emission GCAM-PD scenario increase to 2.4 °C by the mid 21st century. The longer the delay in the transition to a peak and decline scenario, the larger the temperature increases in the interim.

These examples illustrate that it is possible for global emission reductions to ultimately constrain long-term global temperature change to below (or near) a 2 °C threshold value (Fig. 2) by some point in the 22nd century, although the emission reductions required can be large (Fig. 1). Emission reductions, however, cannot ensure that temperature remains below a given threshold at all times if the climate sensitivity is high. This is the situation where SRM techniques might be considered as additional measures to reduce the magnitude of global temperature changes and associated impacts over an interim period.

3 SRM application

The use of SRM is not a binary on or off decision, but a potential response with variations in magnitude and timing. While the details of an SRM application will depend on climate dynamics and the nature of the SRM technique used, the overall scale of SRM will depend on the amount of temperature change that would need to be offset. To quantify the amount of SRM that would be needed to meet a given target, we introduce a "degree-year" metric, which is the integral over time of the amount global mean temperature exceeds a given threshold, adjusted for climate sensitivity:

$$SRM\ Degree-Years = \sum (\Delta T - \Delta T_{threshold})/Normalized\text{-}Climate\text{-}Sensitivity, \quad (1)$$

where the Normalized-Climate-Sensitivity is the climate sensitivity divided by a reference value of 3.0 °C per CO_2 doubling. The degree-year metric is scaled by the climate sensitivity because, at a larger climate sensitivity, it will take proportionally less radiative forcing reduction to affect a given reduction in temperature. This follows from the definition of climate sensitivity: $\Delta T \propto$ climate-sensitivity • radiative-forcing.

Note that the degree-year metric is only well defined if the long-term temperature-change in a given scenario eventually falls below the threshold. This is equivalent to requiring that SRM not be needed indefinitely (or, at least over the 300 year time span of this anaylsis), which is, arguably, consistent with a long-term goal of stabilizing the climate system. In all cases shown in Table 2, both the reference and stabilization (RCP4.5-stab) scenarios exceed the specified thresholds throughout the modeled period. Because they generally exceed the thresholds for some hundreds of years, the degree-year metric is effectively, infinite and is, therefore, not shown.

Figure 3 and Table 2 show the number of degree-years a 2 °C temperature threshold is exceeded as a function of emission scenario and climate sensitivity. Degree-years increase with climate sensitivity and also with the amount of delay in moving to a peak and decline scenario. The primary determinant of the magnitude of potential SRM is the climate sensitivity. If the climate sensitivity is low, then global temperature change does not exceed 2 °C for the GCAM-PD or any of the three PD transition scenarios. In the emission scenario with a transition to a peak and decline trajectory after 20 years (Stab->PD_20yr), for example, the degree-year metric ranges from zero at a climate sensitivity of 2.5 °C/CO_2 doubling or below to 49 degree-years at a climate sensitivity of 4.5 °C/CO_2 doubling. The degree-year metric for other global mean temperature threshold values are shown in Table 2.

Figure 4 shows a sample application of SRM for the Stab->PD_20yr scenario (see ESM). In this case a constant forcing reduction of −0.90 W/m² is applied from 2040 through 2110 (ramping up from zero in 2030 and down to zero in 2120). This mangitude was chosen iteratively as the value that reduces global mean temperature change below a 2 °C threshold under a climate sensitivity of 4.5 °C/CO_2 doubling. 0.90 W/m² is only 24 % of the CO_2 doubling forcing of 3.7 W/m². Because global temperatures respond quickly to a forcing reduction (Matthews and Caldeira 2007), temperature increase is slowed once SRM is initiated. As a result of the assumed forcing offset, global average temperatures are reduced to near 2.0 °C throughout the period shown.

The peak magnitudes of the SRM applied here are broadly similar to those found by Boucher et al. (2009), although SRM is applied here over a shorter period of time. Note that Boucher et al. considered stabilization scenarios, which do not meet the long-term temperature change goals discussed here.

Table 2 Values for the degree-year metric for global temperature change threshold values ranging from 1.9 to 2.2 °C relative to preindustrial and for climate sensitivity values ranging from 2.5 to 4.5 °C/CO_2 doubling. The metric for the 1.9 °C threshold case is approximate for two of these scenarios because temperatures are above this level in 2300 (see ESM)

Climate sensitivity	Scenario	Threshold			
		1.9 °C[*]	2 °C	2.1 °C	2.2 °C
CS2.5	Stab->PD_30yr	1	0	0	0
	Stab->PD_20yr	0	0	0	0
	Stab->PD_10yr	0	0	0	0
	PD (Peak & Decline)	0	0	0	0
CS3.0	Stab->PD_30yr	18	10	5	1
	Stab->PD_20yr	10	4	0	0
	Stab->PD_10yr	3	0	0	0
	PD (Peak & Decline)	0	0	0	0
CS3.5	Stab->PD_30yr	35	27	19	13
	Stab->PD_20yr	26	18	11	6
	Stab->PD_10yr	17	10	5	1
	PD (Peak & Decline)	3	0	0	0
CS4.0	Stab->PD_30yr	51	42	34	27
	Stab->PD_20yr	41	32	25	18
	Stab->PD_10yr	31	23	16	10
	PD (Peak & Decline)	12	6	3	0
CS4.5	Stab->PD_30yr	70	57	47	39
	Stab->PD_20yr	65	49	38	30
	Stab->PD_10yr	56	39	29	21
	PD (Peak & Decline)	30	16	9	5
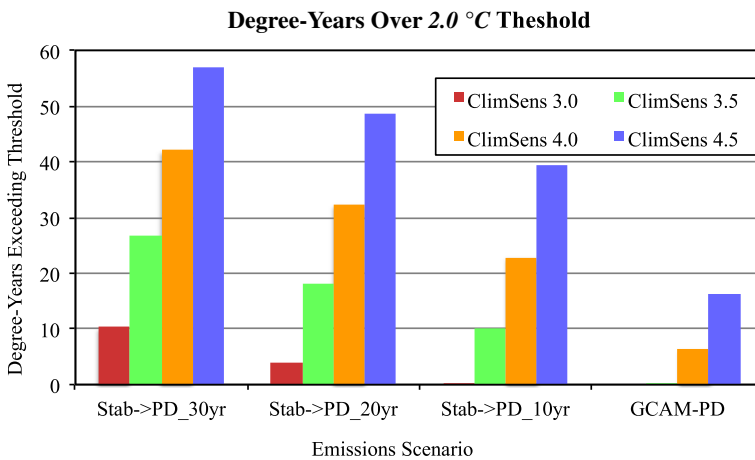
Fig. 3 Degree-years of SRM offset needed to keep global mean temperatures below a 2 °C threshold for climate sensitivities ranging from 3.0 to 4.5 °C per CO_2 doubling (Eq. 1). Degree-years are zero in all of the scenarios shown in this figure for climate sensitivities of 2.5 or 2.0

Global Temperature Change with SRM

Stab->PD_20yr Scenario
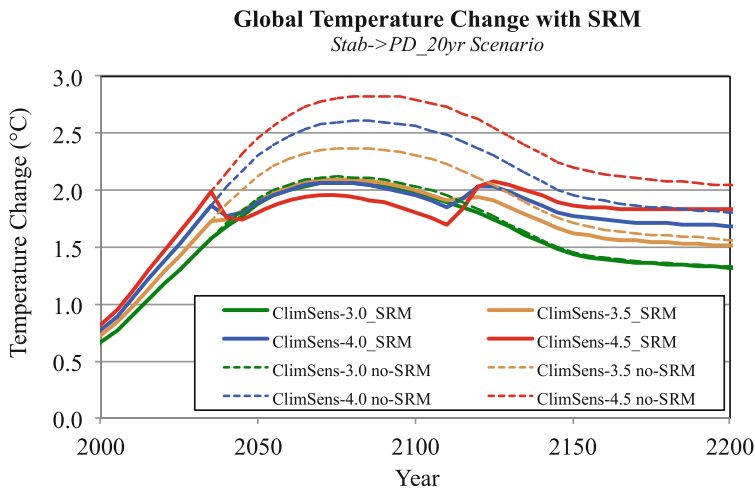
Fig. 4 Global mean temperature change from pre-industrial levels with (*solid lines*) and without (*dotted lines*) the addition of a constant radiative forcing reduction through SRM from 2040 to 2110 for the Stab->PD_20yr scenario for climate sensitivities of 3.0 through 4.5 °C per CO_2 doubling

Figure 4 also shows that scaling the applied SRM with the degree-year metric for other values of the climate sensitivity results in similar global mean temperature changes over the 2040–2110 period over which SRM is applied. This required an applied SRM of −0.60, −0.33 W/m^2 and −0.07 W/m^2 respectively, which is 16 %, 9 % and 2 % of CO_2 doubling forcing. Long-term temperatures, and to a lesser extent CO_2 concentrations, are sightly lower even after SRM is decreased due to ocean thermal inertia and feedbacks, which constitutes and additional long-term benefit of SRM application (see ESM).

The increase in temperatures after 2110 is due to the assumed cessation of the SRM. While the SRM application can, in principle, be "tuned" to provide a specified temperature pathway, a constant level of SRM was used for simplicity. Note also that natural variability would likely obscure some of the potential effect of SRM and any such "fine tuning" (MacMynowski et al. 2011).

4 Implications

Unless the climate sensitivity is low, some sort of peak and decline emission scenario is likely necessary to limit global mean temperature change to 2 °C over the long-term (e.g. Fig. 2). Under any of the peak and decline (PD) scenarios examined here, global temperature change would be near or under 2 °C by the end of the 22nd century (Fig. 2), meeting current policy goals (at least if the climate sensitivity is less than 4.5 °C).

If the climate sensitivity is well below the current central estimate of 3.0 °C per CO_2 doubling, it is possible to keep global mean temperatures below a 2 °C threshold at all times through mitigation actions. SRM would not be needed in this case.

If the climate sensitivity is near the current central value, temperature change might increase modestly above 2 °C before then declining in the PD mitigation scenarios considered here. The impacts due to a limited duration of temperature increase over

2 °C might be small enough to be tolerable. The potential need for SRM is ambiguous in this case.

If climate sensitivity is high then some intervention such as SRM would be needed to keep temperature change below a 2 °C target level, even in aggressive emission mitigation scenarios. Delays in moving from a stabilization to a peak and decline scenario would result in increased climate impacts, which would result in an increased need for SRM if global temperatures were to be limited to under 2 °C. Regardless of the use of SRM, however, a long-term reduction in greenhouse gas emissions is needed to stabilize, or reduce, carbon dioxide concentrations.

While scenarios in the literature have often examined SRM of sufficient magnitude to counter current anthropogenic forcing or a future CO_2 doubling (Bala et al. 2008; Matthews and Caldeira 2007), the magnitude of SRM needed if used in conjunction with emission mitigation is generally much lower, as also noted by Wigley (2006). A forcing offset only 2–24 % of CO_2 doubling forcing, depending on the climate sensitivity, would bring global mean-temperature change down to near 2 °C in the Stab->PD_20yr scenario (Fig. 4). This conclusion is consistent with the results of Goes et al. (2011), who examined decision-making under a range of uncertainties. Existing analysis of the climatic impacts of SRM are, therefore, overestimated relative to a context where SRM is coupled with substantial greenhouse gas emission mitigation. This analysis highlights the need to examine the potential magnitude of these changes in an appropriate context. An important issue with a relatively low level of SRM application, however, is that it may take decades to observationally verify effectiveness (MacMynowski et al. 2011).

It is important to note that SRM will not exactly counter greenhouse gas forcing due to different spatial and spectral characteristics (Bala et al. 2008; Rasch et al. 2009). SRM will therefore cause climate changes itself. The character of these changes would need to be much better understood before SRM should be considered (Climate Institute 2010).

The illustrative calculations presented here did not include any strongly non-linear earth-system responses, loosely referred to as "tipping points", such as a large release of carbon dioxide or methane from natural ecosystems as temperatures increase (Lenton 2011). Reducing the likelihood of such responses is one potential motivation for emission mitigation in general and, perhaps, for SRM in the interim.

In conclusion, SRM might be needed if the climate sensitivity is high or if some key impact is highly sensitivite to climatic changes. Even under these circumstances, SRM would, at least for the thresholds examined here, not be needed immediately. Our analysis suggests there is time to research risks and benefits, and also to put into place the appropriate observational systems for monitoring climate impacts in general and SRM in particular. The possible use of SRM, however, should be examined in the context of substantial, long-term emission reductions, along with the consequent adaptation that would be required for remaining climate changes. The conditions under which SRM might be considered are the same conditions that require substantial emission reductions in order to meet stated policy goals. The imperfect compensation of SRM means it does not substitute for emission reductions and further analysis of SRM coupled with mitigation scenarios is needed. Policy measures to tie potential SRM use to long-term emission reductions could also be considered.

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