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Implications of delayed actions in addressing carbon dioxide emission reduction in the context of geo-engineering

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Abstract Carbon dioxide emissions need to be reduced well below current emissions if atmospheric concentrations are to be stabilised at a level likely to avoid dangerous climate change. We investigate how delays in reducing CO_2 emissions affect stabilisation scenarios leading to overshooting of a target concentration pathway. We show that if geo-engineering alone is used to compensate for the delay in reducing CO_2 emissions, such an option needs to be sustained for centuries even though the period of overshooting emissions may only last for a few decades. If geo-engineering is used for a shorter period, it has to be associated with emission reductions significantly larger than those required to stabilise CO_2 without overshooting the target. In the presence of a strong climate–carbon cycle feedback the required emission reductions are even more drastic.

1 Introduction

Carbon dioxide (CO_2) emissions due to fossil fuel burning and changes in land use provide the largest contribution to the observed increase in global average surface temperature of approximately 0.7°C since pre-industrial times. With further emissions of CO_2 and greenhouse gases in the future it is predicted that, in the absence of climate mitigation policies, the global surface temperature could increase by an additional 1.1°C to 6.4°C by the end of the twenty-first century depending on the scenario under consideration, climate sensitivity, ocean heat uptake and strength of the climate–carbon cycle feedback (IPCC 2007). Over the next several centuries carbon dioxide is likely to remain the single most important anthropogenic

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greenhouse gas. Its relatively poor radiative efficiency is more than compensated by large emissions and a long lifetime in the atmosphere. Mitigation policies are needed if atmospheric CO_2 concentrations are to be stabilised at levels for which the climate response is deemed to remain "acceptable". At present there is no consensus as to the level of warming or atmospheric CO_2 concentration that would achieve this, although the European Union has adopted a target of 2°C above pre-industrial levels (den Elzen and Meinshausen 2006). A range of concentrations pathways have been proposed to stabilise CO_2 at levels of between 450 and 1,000 ppm over a few centuries. Scenarios SP450, SP550, SP650, SP750 and SP1000 have been constructed, ensuring a splined increase from observed concentrations to stabilisation (Enting et al. 1994). All these scenarios require significant emission reductions over the next few centuries. Some more recent studies suggest even more aggressive emissions reductions might be required if there is a significant climate–carbon cycle feedback (Jones et al. 2006b). It is noteworthy that the conversion of a concentration pathway to an emission pathway depends on the carbon cycle model considered and is fraught with uncertainties on both the carbon–climate feedback and the predictions of global and regional scale climate change (Jones et al. 2006b). Although we focus on CO_2 in this paper, it is clear that a multi-gas strategy also involving other non-CO_2 greenhouse gases—and possibly some short-lived species as suggested by Hansen et al. (2000)—would offer more flexibility towards mitigation of climate change. However sizeable CO_2 emission reduction would still be needed if we are interested in time scales of more than a few decades.

Although mitigation of climate change is likely to be best achieved by lowering emissions of greenhouse gases it has also been argued that this may be technologically and economically difficult and that geo-engineering the Earth's climate should also be considered. A range of options has been proposed in the literature (Budyko 1977; Dickinson 1996). However, apart from carbon capture and geological sequestration, most geo-engineering proposals are about intentionally modifying the Earth's energy balance in a way that counteracts the additional greenhouse effect due to human activities (NASA 2007). The debate about geo-engineering has been recently reactivated by Crutzen (2006) who suggested that the scientific community should investigate the positive and negative side effects of injecting sulphur into the stratosphere in order to increase the Earth's albedo and cool the climate system (see also the comments by Bengtsson 2006; MacCracken 2006; Cicerone 2006). Rasch et al. (2008) further examined the pattern of climate change associated with stratospheric injection of sulphur. Their model indicates that during winter mid-latitude and polar regions do not cool as much as the rest of the world in response to stratospheric aerosols. Rasch et al. also showed that the increased mass exchange between the stratosphere and troposphere under a warmer climate shortens the residence time of stratospheric aerosols and requires a larger injection rate of sulphur. Finally they pointed out to the importance of the aerosol size in determining the radiative efficiency of stratospheric aerosols. Tilmes et al. (2008) showed that large artificial injection of sulfur in the stratosphere would cause significant Arctic ozone depletion and would delay the recovery of the Antarctic ozone hole.

Wigley (2006) further argued that mitigation and geo-engineering could be combined to stabilise the climate but did not examine systematically how geo-engineering can be used to offset the long-term effects of overshooting emissions. Wigley (2006) considered the combination of a concentration overshoot scenario—eventually

stabilising at 450 ppm—and a low, medium or high intensity geo-engineering option. His low geo-engineering case ramps up and down over a period of 80 years, which delays future warming but results in a much steeper temperature increase afterwards. The medium and high geo-engineering cases lead to temperature stabilising at 1°C or −0.5°C relative to 2000 but they have to be sustained indefinitely. Moreover CO_2 emissions have to be roughly zero from 2150 to 2250 to offset the initial overshoot. This is consistent with the results from Matthews and Caldeira (2008) who showed that emissions reductions had to continue in the longer term and emissions should eventually be reduced to near-zero to stabilise the climate. Matthews and Caldeira (2007) further showed that the climate system responds quickly to a reduction in insolation so that geo-engineering can be delayed until it is absolutely needed. However they also show that, if CO_2 emissions continue to increase, failure or interruption of the geo-engineering would lead to very rapid climate change, with warming rates up to 20 times greater than present-day rates.

Geo-engineering encompasses many scientific, technical, ethical and societal facets and it is not our purpose to discuss all these issues here. In this work we look at emissions reductions required to stabilise CO_2 concentrations. We focus here on stabilisation scenarios at 550 ppm (as a low-end but realistic mitigation scenario) and 750 ppm (as a high-end mitigation scenario). We first investigate the consequences of delaying the CO_2 emissions reductions by one to four decades before coming back to the desired emission pathway. We then investigate the consequences of delaying the CO_2 emissions reductions by the same amount but returning back to the desired CO_2 concentration pathway. We then work out what the implications are if we rely on geo-engineering to compensate for such a delay in emissions reductions. We discuss what the implications of the long response times of the carbon cycle and climate system are for geo-engineering options. This issue is mentioned by Bengtsson (2006) but has been otherwise overlooked by most geo-engineering studies so far.

2 Methods

We base our analysis on simple carbon cycle and climate models which use impulse response functions (IRF) to describe the evolution of the atmospheric CO_2 concentration and global surface temperature to CO_2 emissions (Table 1). The parameters in these simple models are derived from simulations with more complex chemistry and climate models. We appreciate that this approach is very simple and is associated with a number of caveats (Joos and Bruno 1996). First it does not account for the

Table 1 Parameters of the impulse response functions used in this study

	$i=0$	$i=1$	$i=2$	$i=3$
a_i (unitless)	0.217	0.259	0.338	0.186
b_i (years)		172.9	18.51	1.186
c_i (K $(Wm^{-2})^{-1}$)		0.631	0.429	
d_i (years)		8.4	409.5	

slow processes governing the CO_2 cycle on very long time scales (Archer et al. 1997). However these slow processes would not play a significant role on the 500-year time scale we consider in this study and it is appropriate to neglect them here. Second the use of an impulse function makes it more difficult to account for the carbon–climate feedback but we present a simple way to estimate the sensitivity of our results to the strength of the carbon–climate feedback. We therefore believe that our approach is sufficient in the current context to support qualitatively and, to some extent, quantitatively our conclusions.

The impulse response function for CO_2 is an update from Joos and Bruno (1996) which has been used in IPCC (2007). It has been estimated from a 400 Gt C impulse emission in the Bern carbon cycle model under conditions of stabilised CO_2 concentrations at 378 ppmv. The fraction of carbon emitted at time $t = 0$ which is left in the atmosphere at time t is expressed as

$$f(t) = a_0 + \Sigma_i a_i \exp\left(-t/b_i\right) \tag{1}$$

with $\Sigma_i a_i = 1$ by construction. The CO_2 atmospheric concentration at time t_1 from an emission profile $e(t)$ can then be approximated as a convolution of $e(t)$ with $f(t)$

$$\left[CO_2\right](t_1) = \left[CO_2\right](t_0) + \int_{t0}^{t1} e(t)\, f(t_1 - t)\,/c\, dt \tag{2}$$

where c is a constant that converts yearly emissions in Gt C to atmospheric concentrations in ppmv (1 ppmv = 2.123 Gt C) and t_0 represents pre-industrial time. By design the CO_2 impulse response function does not account for the fact that both the land and ocean carbon sinks depend on the atmospheric CO_2 concentration and climate change. Accounting for the carbon–climate feedback can result in a significantly larger airborne fraction of emitted CO_2 in a warmer climate (Jones et al. 2006a) as discussed later in this study.

We follow IPCC (2001) and approximate the radiative forcing due to anthropogenic CO_2 as

$$\mathrm{RF}(t) = \alpha \ln\left(\left[CO_2\right](t)/\left[CO_2\right](t_0)\right) \tag{3}$$

with $\alpha = 5.35$.

The climate response (in terms of global surface temperature change) is estimated from an impulse response function to a unit radiative forcing (RF):

$$\delta \mathrm{T}(t) = \Sigma_i\, c_i/d_i\ \exp\left(-t/d_i\right) \tag{4}$$

with the c_i and d_i coefficients given in Table 1. The climate responds with a short timescale d_1—representing the processes associated with the mixed-layer ocean—and a longer timescale d_2—representing the processes associated with the deep ocean. The equilibrium climate sensitivity, as the sum of the c_i coefficients, is 1.06 K $(\mathrm{Wm}^{-2})^{-1}$ or 3.9 K for a doubling of the CO_2 concentration. The impulse response function for surface temperature has been derived from more than 1,000 simulated years of an experiment with the HadCM3 climate model in which atmospheric CO_2 concentrations were quickly ramped up to four times the pre-industrial levels before being held constant. We believe that the experimental setup favouring the longer timescales of the climate response is responsible for the slightly larger climate sensitivity than reported elsewhere for the HadCM3 model. The

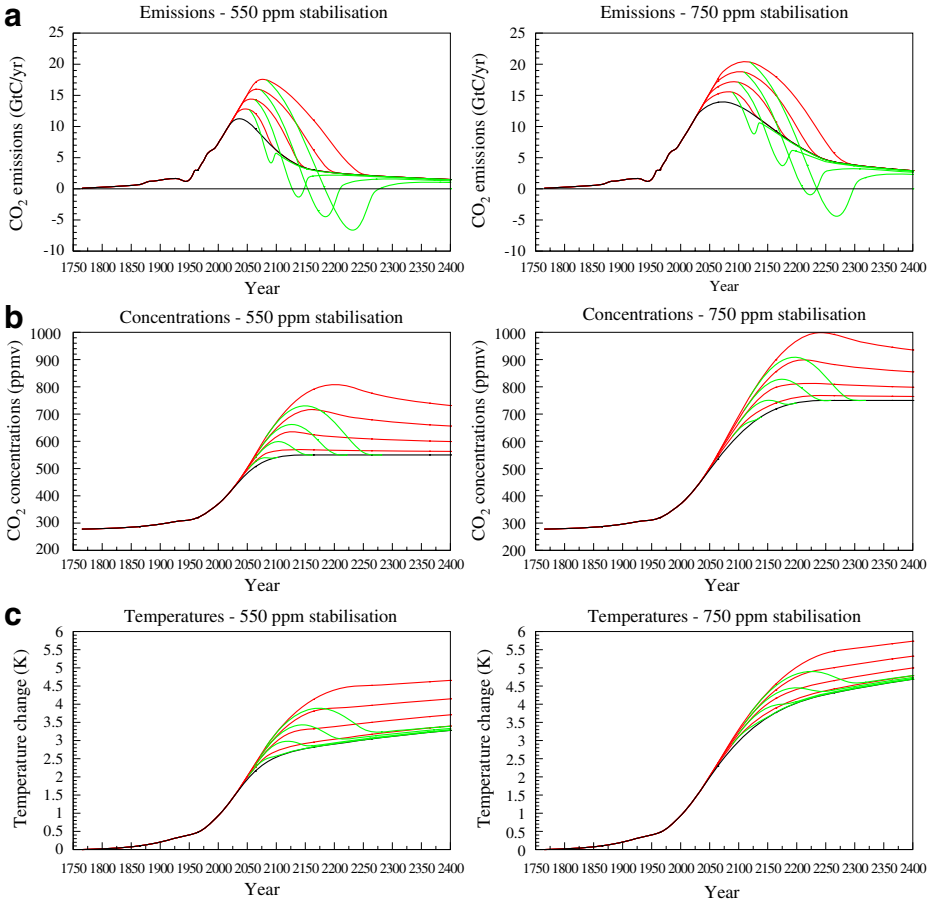

Fig. 1 **a** CO_2 emissions (Gt C/year), **b** CO_2 atmospheric concentrations (ppm), and **c** global temperature change (K) over the period 1750 to 2400. The *black curve* refers to the SP550 (*left*) and SP750 (*right*) stabilisation scenarios. The *four red curves* correspond to lags of 10, 20, 30 and 40 years in implementing a climate mitigation policy and a nudging back to the SP550 or SP750 *emissions* pathways over a period of 50, 100, 150 and 200 years, respectively (experiments from the SP550E*n* and SP750E*n* families). The *green curves* are as the *red curves* but for a nudging back to the SP550 and SP750 *concentrations* pathways instead (experiments from the SP550C*n* and SP750C*n* families)

climate response IRF can then be used to estimate the global surface temperature change between times t_0 and t_1 from a RF profile RF(t) as:

$$\Delta \mathrm{T}\,(t_1) = \int_{t0}^{t1} \mathrm{RF}\,(t)\ \delta \mathrm{T}\,(t_1 - t)\,dt \tag{5}$$

Given the uncertainties in past emissions (especially from changes in land use) and in order to treat the historical and future periods in a fully consistent manner, we do

not reconstruct the CO_2 concentrations from inventories of past emissions. Instead we use iteratively Eq. 2 to calculate the emissions from the observed historical CO_2 concentrations. This is done with a timestep of 1 year and an analytical solution for Eq. 2. With implied emissions of 1.5 and 7.5 Gt C/year in 1950 and 2000, respectively, the estimated emissions for the historical period are somewhat low but within uncertainties of emission inventories (Prentice et al. 2001). In a similar way we estimate what future permissible emissions are in order to match the concentration pathways of the SP550 and SP750 scenarios. These emissions profiles are shown as the black curves on Fig. 1a and correspond to the stabilisation concentration curves of Fig. 1b. Stabilisation at 550 ppm requires a fivefold decrease in emissions in 2400 as compared to 2000. The resulting surface temperature change curves are shown on Fig. 1c as black curves. It can be noted that the global surface temperature continues to increase well beyond the time CO_2 concentrations are stabilised. The global average sea level would increase for even longer (Lowe et al. 2006).

3 Implication of a delay in emissions reductions

We now investigate what the consequences are if there is a delay in implementing CO_2 emissions reductions. We consider four arbitrary variants of the SP550 and SP750 scenarios, for which, instead of decreasing, CO_2 emissions continue to increase during an extra 10-, 20-, 30- or 40-year period. We assume that, during these one to four decades, CO_2 emissions increase at an absolute growth rate taken equal to the maximum absolute growth rate of CO_2 emissions in the respective SP550 and SP750 scenarios. The maximum growth rate is about 0.16 Gt C/year and is found to occur in 2019 and 2022 in SP550 and SP750, respectively. After this period of continuous growth for one to four decades, the year-to-year changes in CO_2 emissions are taken to be the same as in the SP scenarios from the year of maximum growth until 5 years after the year of maximum CO_2 emissions. In other terms we translate the SP emission curves between these two dates horizontally by 10 to 40 years as well as upwards to ensure continuity in the emissions. These extra emissions (in red on Fig. 1a) can then be converted to increased atmospheric concentrations (also in red on Fig. 1b) and surface temperature change (Fig. 1c).

We then assume two different pathways for returning back to the SP scenarios. In a first set of experiments, we nudge the *emissions* to the SP550 or SP750 *emissions* pathways over periods of 50, 100, 150 and 200 years, respectively, for the four variants introduced above (experiments SP550E*n* and SP750E*n* with *n* ranging from 1 to 4). Table 2 and the red curves on Fig. 1 show the details of these experiments. In a second set of experiments, we nudge the *concentrations* back to the SP550 and SP750 *concentrations* pathways over 50, 100, 150 and 200 years (experiments SP550C*n* and SP750C*n* with *n* ranging again from 1 to 4). The nudging to concentrations is done using a smooth function in order to avoid discontinuities in the permissible emissions. We can then infer the permissible emissions for experiments SP550C*n* and SP750C*n* using the same technique and equations as described above for the historical emissions. Results of the SP550C*n* and SP750C*n* families of experiments are shown with green curves on Fig. 1 when they diverge from their SP550E*n* and SP750E*n* counterpart experiments. Permissible emissions are lower than emissions from the SP550 and SP750 scenarios long after the end of the nudging period.

Table 2 Cumulative CO_2 emissions from overshoot and cumulative CO_2 emission reduction required to offset the overshoot for different periods of action delay and recovery under the SP550 and SP750 scenarios

Scenario	SP550				SP750			
	E1/C1	E2/C2	E3/C3	E4/C4	E1/C1	E2/C2	E3/C3	E4/C4
Delay in action	10	20	30	40	10	20	30	40
Period of maximum growth rate	2019–2030	2019–2040	2019–2050	2019–2060	2022–2033	2022–2043	2022–2053	2022–2063
Year of maximum emission	2046	2056	2066	2076	2083	2093	2103	2113
Recovery period (years)	50	100	150	200	50	100	150	200
Beginning of nudging period	2052	2062	2072	2082	2089	2099	2109	2119
End of nudging period	2101	2161	2221	2281	2138	2198	2258	2318
Additional cumulative emissions for the emission (E) nudging case	110	404	852	1419	121	389	816	1393
Additional cumulative emissions for the concentration (C) nudging case	68	243	519	878	87	252	512	865
Additional cumulative emission reductions for the concentration (C) nudging case	64	217	440	702	79	219	420	663
Maximum annual emissions reduction for the concentration (C) nudging case	0.47	0.44	0.41	0.37	0.41	0.37	0.36	0.36

Units for cumulative emissions and emissions reductions: Gt C

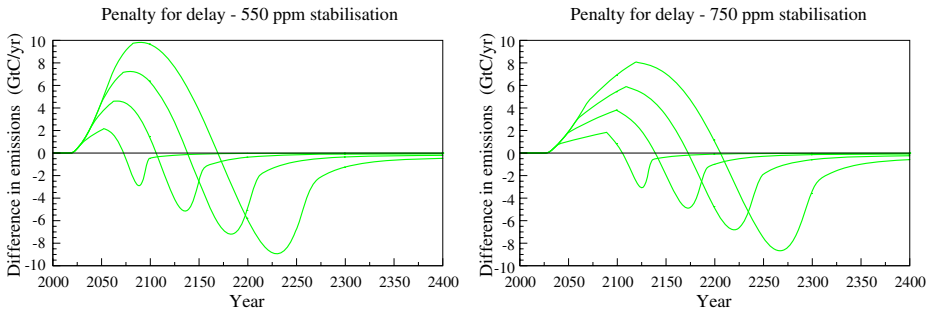

Fig. 2 Difference in emissions (SP550 minus SP550C1/2/3/4 and SP750 minus SP750C1/2/3/4). The negative emissions represent here the "penalty for delay" in moving to stabilisation. Unit: Gt C/year

It is also noteworthy that nudging back to concentrations implies negative emissions for a number of our experiments. The 30-year delay experiment for SP550 and the 40-year delay experiments for SP550 and SP750 require a significant period of negative emissions (up to 7 Gt C/year). The 20-year delay experiment for SP550 and the 30-year delay experiment for SP750 require a few years of negative emissions. This feature was also observed by Jones et al. (2006b) for some parameter combinations when the climate–carbon feedback was included in a model to infer permissible emissions for stabilisation scenario. Without considering any delays in emissions reductions, they found that for some combinations of climate and carbon cycle sensitivity, negative emissions would be required to follow the WRE 450 and 550 scenarios of Wigley et al. (1996). Negative emissions are theoretically possible but would be very difficult to achieve as they correspond to large-scale engineered removal of CO_2 from the atmosphere. One method might be to capture and store carbon emitted by power plants run from biomass (van Vuuren et al. 2007), although the actual potential of this technology is still very uncertain. Negative emissions can be avoided if the nudging back to the concentrations is made stiffer. However this makes it more challenging from a socio-economical point of view because it requires more rapid rates of decrease in emissions.

We also show on Fig. 2 the "penalty for delay" in terms of permissible emissions relative to the stabilisation scenario (i.e. we represent the difference between the SP550/750C*n* and the SP550/750 experiments). Extra emissions over an initial period have to be offset by extra emission reductions later on. Our results are in qualitative agreement with those of Enting et al. (1994) who showed similar "penalty for delay" plots (their Figure 8.5). They are also consistent with the results from Mignone et al. (2008) who showed there was a significant penalty in terms of the peak concentration of atmospheric carbon dioxide when postponing the time of emission reduction. Finally, one should also note that the required cumulative emission reduction to "recover" from the overshoot emissions is always less than the cumulative emissions from the overshoot (compare second and third lines from the end in Table 2). This is because by the time we reduce emissions below the original emission pathway, part of the overshooted emissions have already been sequestered by the land and the ocean, therefore limiting the need to reduce emissions. Note that this conclusion would not necessarily hold if there is a strong carbon–climate feedback. The maximum rate of required emissions reduction is also higher in the overshoot scenarios. The

maximum annual emissions reductions are in the range of 0.36 to 0.47 Gt C/year for our experiments, to be compared to 0.10 and 0.07 Gt C/year in the SP550 and SP750 scenarios. It is beyond the scope of this study to compare the relative benefits of greater allowed cumulative emission and greater required rate of reduction, but this is clearly a critical question for determining any "optimal" mitigation policy. Furthermore, it is clear from Fig. 1 that even though the same concentrations and global temperatures will eventually be reached the delay in emissions reductions will lead to greater and earlier impacts unless the overshoot in temperature is offset in some manner. In the following we discuss the requirements that an offsetting method would need to satisfy.

4 Counteracting a delay in emissions reductions

One may want to counteract the additional climate change caused by delaying CO_2 emission reductions using a geo-engineering option in order to achieve a specific global temperature change target (i.e. the black curve on Fig. 1c). The geo-engineering option would need to offset the additional radiative forcing due to the extra CO_2 emissions by artificially modifying the Earth's radiation balance. We report the required geo-engineering effort in terms of radiative forcing for our set of experiments (red curves on Fig. 3). If no further emission reductions are to be implemented after the emission overshooting period, the geo-engineering effort has to be sustained for centuries because of the long lifetime of atmospheric CO_2. In that sense offsetting additional CO_2 emissions with geo-engineering only can be seen as a long-term commitment that needs to be passed on to future generations. Stopping the geo-engineering at some stage would materialise by additional climate forcing and possibly rapid surface warming and climate change over the following years to centuries.

Alternatively one may argue that geo-engineering should only be a temporary solution to allow buying some time before it becomes easier and cheaper to reduce CO_2 emissions. Geo-engineering and emission reductions can be combined to achieve the same agreed temperature change target. The green curves on Fig. 3 represent the required geo-engineering effort in unit of radiative forcing if the additional emissions

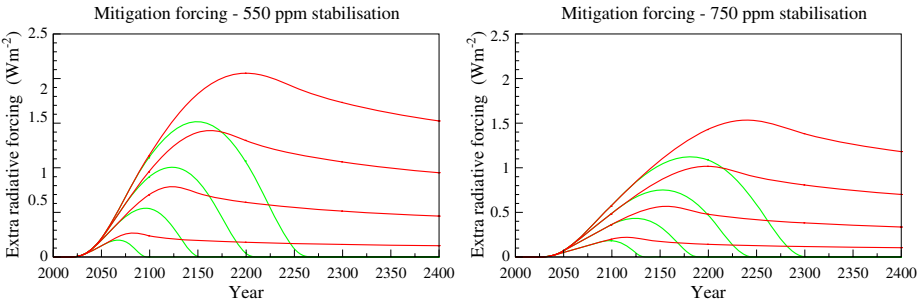

Fig. 3 Radiative forcing (Wm^{-2}) due to the additional CO_2 emissions relative to the original mitigation scenario. The *red* and *green curves* are as for Fig. 1

reductions discussed above are achieved. This shortens the period for which an effort has to be sustained but it makes climate mitigation more demanding from an economical point of view as geo-engineering and emissions reductions have to be implemented at the same time after the initial period of overshooting.

We can roughly estimate the corresponding required loading of stratospheric aerosols needed to offset the radiative forcing shown on Fig. 3. With a net radiative efficiency in the range of −100 to −200 W (g SO_4)$^{-1}$, a radiative forcing of −1 Wm^{-2} would correspond to an average burden of 5 to 10 mg SO_4 m^{-2}. Assuming a residence time of two years in the stratosphere, each unit radiative forcing would require a sustained injection rate of 0.42–0.85 Tg S year^{-1}. Although this emission rate is small as compared to present-day anthropogenic emissions of sulphur dioxide of 50–70 Tg S year^{-1}, it may not be practical to inject such a large mass in the stratosphere. Such an estimate is very sensitive to the size distribution of the stratospheric aerosol because both the radiative impact of the aerosols (in the shortwave and longwave) and the loss term to the troposphere would depend on their size. This rough estimate is in line with the more complicated calculations from Rasch et al. (2008). They found that an injection rate of 1.5 Tg S year^{-1} is enough to balance a doubling of the CO_2 concentration (i.e. a radiative forcing of 3.7 Wm^{-2}) if the particles are small, but an injection rate twice larger may be needed if the particles are of the size observed after large volcanic eruptions.

5 Impact of the carbon–climate feedback

The IRF approach used above will likely lead to a quicker recovery following overshoot as compared to more sophisticated models of the carbon cycle. This is because the IRF does not account for the carbon–climate feedback, which although uncertain, is likely to be positive and introduces uncertainty in the rate of recovery of atmospheric CO_2 concentration after overshooting. In order to understand the effect the carbon climate feedback could have on our results, we have repeated some of the experiments above with the simplified carbon cycle model described in Jones et al. (2003). The simplified carbon cycle model is a box model representing the vegetation, soil, and oceanic carbon pools and the fluxes to the atmosphere as a function of the atmospheric CO_2 concentration and global surface temperature change. The simplified model has been tuned to reproduce the results of the HadCM3LC model which shows the largest feedback under the C4MIP exercise (Friedlingstein et al. 2006). We have run the simplified model under the SP550 scenario with and without the temperature feedback on the carbon cycle. We recalculated the anthropogenic emissions required to fit the SP550 concentration pathway with the simplified model with and without the climate influence on the carbon cycle. The permissible emissions are much lower if the carbon–climate feedback is accounted for as already shown in Jones et al. (2006a, b). We investigate here how the climate–carbon cycle feedback affects the "penalty for delay" discussed earlier. We have retuned the rate of CO_2 emissions during the overshooting period so that the additional cumulative emissions for the concentration-nudged cases are the same as in Table 1 in the two runs with and without the climate influence on the carbon cycle. The effect of the carbon–climate feedback is to increase the additional cumulative CO_2 emission reduction required to return to the SP550 concentration pathway after the concentration

and temperature overshooting. The additional cumulative CO_2 emission reduction increases from 66.7 to 67.3 Gt C year^{-1} in the SP550C1 scenario, from 235 to 237 Gt C year^{-1} in SP550C2, from 494 to 500 Gt C year^{-1} in SP550C3 and from 820 to 834 Gt C year^{-1} in SP550C4. In other terms there is an additional penalty for delaying emissions because the overshoot in temperature is responsible for decreased uptake from vegetation and soil. The higher the stabilisation level is, the larger this penalty is.

6 Discussion and conclusions

We have examined what the long timescales associated with the carbon cycle mean for geo-engineering options in the context of two CO_2 stabilisation scenarios. We showed that overshoot emissions for a period of decades would need to be offset by geo-engineering for a period of centuries. Alternatively geo-engineering can be stopped after a period of 100 to 250 years provided further emission reductions than implied by the mitigation pathway are achieved in the period immediately following the overshooting. We argue that the cost of and commitment to geo-engineering needs to be estimated on very long time horizon.

This study did not address the potential side effects of geo-engineering options. These may be significant with potential responses from the general atmospheric circulation, atmospheric chemistry, and the biosphere and human health. Such responses would need to be studied in great detail. There are also ethical and social acceptance issues. The models used here and elsewhere are ultimately simplifications of the real climate and depend on uncertain parameters. We have presented a scenario for a plausible set of parameters but would recommend a much more thorough risk analysis that considers the uncertainties associated with unintentional and intentional climate intervention if geo-engineering is considered more seriously. The consequences of stopping a geo-engineering option also need to be investigated.

Finally it is important to note that the direct effects of increased CO_2 atmospheric concentration on the continental and oceanic biosphere would not be avoided by a climate engineering option that targets only a change in the Earth's radiative balance. Carbon dioxide is expected to fertilise the continental biosphere, with the potential for more carbon sequestration in the vegetation and soil, but also unclear effects on biodiversity and soil composition and quality. The CO_2 physiological effect on plants has already been detected on river runoff (Gedney et al. 2006). It induces a complex climate response involving increased surface temperature and lapse rate as well as increased specific humidity and induced greenhouse effect over some regions (Boucher et al. 2008). It may also decrease surface deposition of ozone with associated air quality and climate implications (Sanderson et al. 2007). Moreover increased atmospheric concentrations of CO_2 will acidify the ocean with impacts on marine plankton species (Orr et al. 2005). Geo-engineering the Earth's radiative balance would therefore not prevent the direct impacts of high atmospheric CO_2 concentration whether they are positive or negative.

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