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If climate action becomes urgent: the importance of response times for various climate strategies

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Abstract Most deliberations on climate policy are based on a mitigation response that assumes a gradually increasing reduction over time. However, situations may occur where a more urgent response is needed. A key question for climate policy in general, but even more in the case a rapid response is needed, is: what are the characteristic response times of the response options, such as rapid mitigation or solar radiation management (SRM)? This paper explores this issue, which has not received a lot of attention yet, by looking into the role of both societal and physical response times. For mitigation, technological and economic inertia clearly limit reduction rates with considerable uncertainty corresponding to political inertia and societies' ability to organize rapid mitigation action at what costs. The paper looks into a rapid emission reductions of 4–6 % annually. Reduction rates at the top end of this range (up to 6 %) could effectively reduce climate change, but only with a noticeable delay. Temperatures could be above those in the year of policy introduction for more than 70 years, with unknown consequences of overshoot. A strategy based on SRM is shown to have much shorter response times (up to decades), but introduces an important element of risk, such as ocean acidification and the risk of extreme temperature shifts in case action is halted. Above all, the paper highlights the role of response times in designing effective policy strategies implying that a better understanding of these crucial factors is required.

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1 Introduction

Most climate change mitigation scenarios have concentrated on long-term, gradual emission reduction, implicitly or explicitly assuming that an optimal climate response can be determined by weighing the costs of mitigation over long time periods against the risks of climate change impacts and/or adaptation costs (Fisher et al. 2007). Such a 'conventional' response strategy can be effective if climate change forms a gradual process, for which it is possible to make a long-term assessment of impacts and expected costs (Charlesworth and Okereke 2009). Most of these scenarios (sometimes called 'first-best' scenarios) show that, in such a situation, it is possible to replace existing greenhouse gas (GHG) emitting infrastructure by a 'low carbon society' infrastructure at costs that are estimated to be less than a few per cent of GDP, although the required changes will still be substantial (Clarke et al. 2010; Van Vuuren et al. 2007). There are several reasons, however, why reality may not develop along this pathway. First of all, it is questionable whether society will be able to account for such long-term considerations, as, for instance, shown by the slow progress in international negotiations and current emission trends (Anderson and Bows 2008; Raupach et al. 2007). One complication is that observable, univocal signs of climate change are likely to only appear with such delay (given fundamental inertia and uncertainties) that it could be too late for acting (Solomon et al. 2009). Here, also the discovery of catastrophic climate impacts or tipping points, such as release of large amounts methane from tundra, dieback of the Amazon forest, rapid disintegration of the Greenland or West Antarctic Ice Sheets (see for instance Lenton et al. 2008; Malhi et al. 2008; Oppenheimer and Alley 2004; Oppenheimer and Alley 2005), or abrupt temperature increase in case the current period of reduced solar activity is followed by a period of increased activity could play a role. If signs of dramatic climate change impacts would become apparent, certainly in a situation of delayed response, society could be faced with the question whether a rapid response would still be effective.

For climate policy-making in general, but even more for a 'rapid response' situation, it is essential to have information on the 'response times' of the various options at hand. We introduce the term 'response time' here referring to the time between the introduction of the measure and a noticeable, substantial shift in climate change trends (or its impacts). Possible measures that may be considered in the situation where a rapid response is needed include fast introduction of new technologies to mitigate emissions, geoengineering[1], rapid lifestyle changes and rapid adaptation. The response time of each of them depends on a wide range of different factors, including technical, socio-economic and political constraints but also climate system parameters. The amount of attention paid to transition rates (either under normal circumstances or in rapid response situation) is still limited. This is partly due to the fact that several relevant factors (such as the timing involved in policymaking) require combinations of various fields of knowledge, including non-quantitative information (typically not covered in models). Still, we feel that gaining more insight in typical response times and the consequences of these will constitute an important research topic in the coming years. Differences between the response times of different options can be a reason to develop certain options to have them available when needed.

For this paper, we concentrate on the response times of a mitigation strategy, based on balanced reduction of CO_2 and non-CO_2 gases and confront this with the possible response

[1] Geo-engineering is a generic terms for all kinds of response options with very different characteristics. Two broad categories are carbon dioxide removal (CDR) and solar radiation management (SRM). In this paper we focus on the second type of measures. Therefore, in the remainder of the paper will specifically refer to solar radiation management (SRM) and avoid the term geo-engineering as far as possible.

times of a second strategy, i.e. solar radiation management (SRM). We partly base our assessment on available historical statistics or scenario information. We also make use of simple calculations using (parts of) the integrated assessment IMAGE model (Bouwman et al. 2006). Given the different nature of these strategies, in particular SRM, we also evaluate some of the other consequences of these strategies. These consequences have been discussed in the literature (see further in this paper), and we relate them through simple experiments to the scenarios discussed here. The analysis needs to be interpreted mostly in qualitative terms, as especially the delays involved in the human system can now only be speculated about. In that light, it is not our intention to provide a final answer but rather to highlight the importance of this research area.

The Integrated Assessment framework IMAGE (Bouwman et al. 2006) consists of model components describing the energy system, land use, the global carbon cycle, and the climate system. The climate model is formed by the MAGICC model (Wigley and Raper 2001) (Meinshausen et al. 2011), describing atmospheric composition and the thermal response of the atmosphere–ocean system, calibrated to represent the behaviour of more complex climate models. The potential for emission reductions is described in various subcomponents of IMAGE, and has been described elsewhere (Van Vuuren et al. 2007). In the model experiments, we assumed, for simplification, that, up to 2030, no climate policy will be introduced (results will not be very different if one instead assumes an introduction of a mild climate policy, such as the current pledges, up to 2030). Next, we assumed that by 2030, society would have tangible evidence of impending dramatic impacts and would therefore introduce drastic measures based on either mitigation or SRM. The focus of our analysis is on the response time of the various options. The calculations were done under a climate sensitivity of 4.5 °C. This value represents the upper end of the "likely" range for the climate sensitivity as assessed by IPCC's 4th Assessment Report (but it should be noted that even higher values cannot be ruled out given the long tails in most of the estimated probability density functions for climate sensitivity). This value was chosen as it seems more likely that rapid response strategies are needed in case of strong climate change, but our results and conclusions will not be very different in qualitative terms for lower or even higher climate sensitivities.

In Section 2 of the paper, we first discuss the characteristic response time of rapid mitigation strategies. In Section 3, we discuss the characteristic response times of SRM strategies. In Section 4 we assess the response times of the climate system to rapid mitigation and SRM. Finally, conclusions are drawn in Section 5. This section also represent an uncertainty analysis covering a fuller range of reduction rates.

2 Rapid mitigation

The effectiveness of a rapid mitigation response to slow down climate change depends both on the maximum emission reduction rate and climate system parameters. Clearly, the first factor cannot be determined unambiguously. This rate is not bounded by laws of nature, but instead depends on the combination of many malleable factors, such as the inertia involved in decision-making processes and in changing investment decisions and behaviour, the capital turn-over rate, the development of new technologies, and inertia in expanding production capacity for new technologies (e.g., available companies able to install insulation, but also the time to train more insulation installers).

Several papers suggest that there are clear limits to the rates of change. Looking at historical rates of technology deployment in the energy system, Kramer and Haigh (2009) suggested that limits to the rate with which new technology could be employed would function as empirical laws on the speed of transition processes. Grubler (2012) reviewed some of the available research on historical energy transitions emphasizing that these transitions have often taken many decades or even more than a century. Factors that have determined the speed of these transition include the lifetime of technologies and infrastructure, scale, market size, technological interrelatedness, the existence of niche markets, and the relative advantage of new versus incumbent technologies (Grubler 2012; Rotmans and Loorbach 2009; Wilson and Grubler 2011). Regarding the first factor, the lifetimes of machinery and infrastructure are often decades or even up to centuries themselves: around 20–40 years for manufacturing equipment and power stations, multiple decades for urban infrastructure, up to 20 years for heating devices and maybe 10 to 20 years for passenger vehicles but much longer for the related infrastructure (Philibert 2007). If mitigation strategies aim to avoid premature capital replacement, which is often considered to be very expensive, it is clear that replacement will take considerable time. An average lifetime of 30 years, for instance, leads in the first decades after introduction to maximum replacement rate of around 3–4 %. Obviously, it is in principle possible to depreciate capital at an increased rate and thereby achieve higher emission reductions. One could even beyond this: analogies have been made to the industrial transformation in the USA during the second world-war (Baer et al. 2009), but so-far no clear conclusions have been drawn on the quantitative implications of such an analogy.

One way to obtain some idea on the maximum reduction rate for CO_2 emissions from fossil-fuel combustion (the lion's share of GHG emissions) is by looking at the existing literature on mitigation scenarios. It should be realized that models used to generate these scenarios only capture some of the relevant dynamics discussed above (while limitations posed by capital turn-over times are often included, other processes are only implicitly in these models at best). The numbers discussed here are therefore only meant to be indicative. We used the database of mitigation scenarios as used for IPCC's 4th Assessment Report (Nakicenovic et al. 2006) and extended it with data on scenarios in recent publications (Clarke et al. 2010; Edenhofer et al. 2010; Rao et al. 2008). In this set, we looked at the rate of CO_2 emission reduction for scenarios in the lowest radiative forcing category characterized in AR4, i.e. lower than 3 W/m^2 by 2100 (Fisher et al. 2007). Although these are 'conventional' scenarios, they are often regarded as being close to the maximum that could be achieved. For each scenario, Figure 1 shows the 10-year average emission reduction rates in the 2010–2100 period, as well as the reduction rates over 50-year and 90-year periods. For the 50 years average rate the highest values are in the order of 3.5 % per year. For the 10-year average rate, the highest values found in the literature are in the order of 4–6 % per year (relative to 2000 emissions). It should be noted that a global reduction rate of 4 % would require an actual decarbonisation rate (change in carbon intensity, expressed as the ratio between the change in CO_2 emissions and economic growth) of almost 6 %, assuming an annual GDP growth of 2 % (a 6 % reduction rate would correspond to a decarbonisation rate of nearly 8 %).

We can now also make a quantitative comparison with the historical information. Historically, the global decarbonisation rate has been around 0.5 % over the period 1900–2010 and around 1 % over the 1970–2010 (driven by technological improvement and sectoral shifts). In terms of 5-year running averages, the global carbon intensity declined most rapidly during the brief period from 1981 to 1985 by about 2–3 % per year in response to high oil prices and related energy policies. Some Asian regions reached historically very high decarbonisation rates of 3–5 % per year during the late 1980s /early 1990s, in a period of even more rapid economic growth leading still to a net growth of emissions. In other words, decarbonisation rates of 6–8 % over sustained periods of time would clearly be unprecedented in history. However, it should be noted that reducing GHG emissions has historically not been a policy objective. It is, therefore, more useful to compare the transition

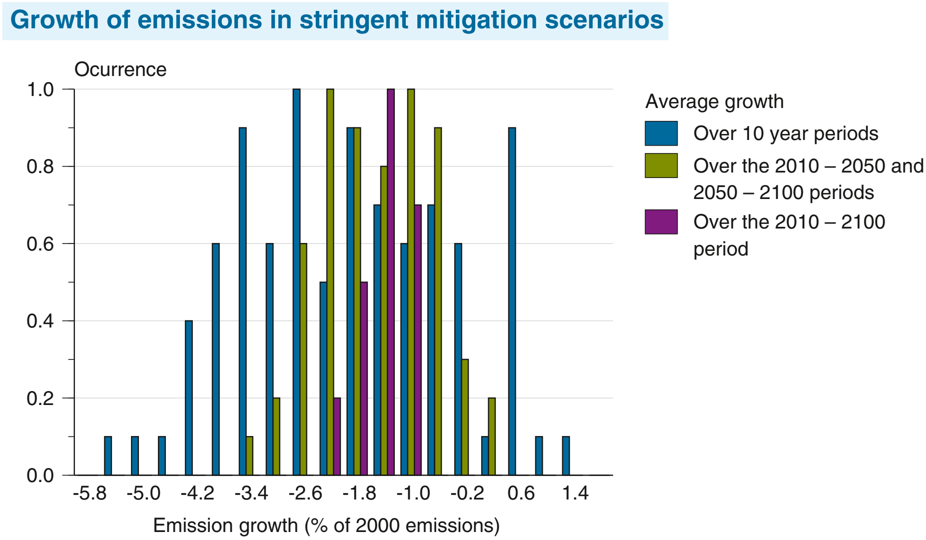

Fig. 1 The occurrence of different growth rates of global CO_2 emissions (expressed as percentage of 2000 emissions) in the lowest mitigation category of IPCC (corresponding to scenarios stabilising greenhouse gas concentration at 2.5 to 3.0 W/m^2). Negative numbers indicate emission reduction. Occurrence is normalised to the highest value found for each sample. The data set includes 27 recent model runs, from the model comparison projects as part of EMF-22 and ADAM. Data is based on the 2010–2100 period, and shows growth rates over 10 year periods, 40/50 year periods and the full 90 year period (see legend)

to non-CO_2 emitting technologies to other major historical transitions: from traditional fuels to coal and from coal to oil and gas. Compared to these earlier transitions, the new transition to non-CO_2 energy technologies described in the most ambitious mitigation scenarios in literature is more comparable: while in the scenarios the share of non-CO_2 emitting technologies needs to grow in the next 5–6 decades from less than 10 % to over 80 %, it took oil and gas from 5 decades (1920 to 1970) to extend their share from 10 % to 60 %. It should be noted that the historical transition was arguably less forced by government policies, but in contrast was driven by more ‘endogenous’ economic and convenience-related factors.

On the basis of this discussion, we conclude that emission reduction rates of 4–6 % globally can be regarded as extremely rapid (in the discussion section, we explore the impacts of using different reduction rates consistent with Fig. 1). In order to find out whether models would be capable of reproducing such a high reduction rate, we simulated a rapid response scenario in the integrated assessment model IMAGE by instantaneously bringing the carbon price to a very high value. For IMAGE, such a tax is 1000 US$/tC. In such a situation, the model reduces (at least initially) CO_2 emissions at a rate bounded only by the lifetime of the capital stock. The results of such a run for the IMAGE model, in terms of the overall reduction rate (resulting from the responses in different sectors in the model) is shown in Fig. 2. For the standard model set-up, the calculations showed that in the first 30 years after the introduction of the carbon price, a maximum reduction rate of 3–4 % per year (as percentage of 2000 emissions) was achieved. This rate goes up to around 5 % per year if the option of bio-energy with carbon capture and storage (BECCS) is also applied (see also Van Vuuren et al. 2007), allowing for negative emissions in the power sector. Clearly, these IMAGE results are consistent with the numbers discussed above. The results of our experiment can therefore be used as representative of the most rapid reduction rates found in the literature. As indicated, real-world emission reduction may be different. While premature capital depreciation or lifestyle change could result in faster

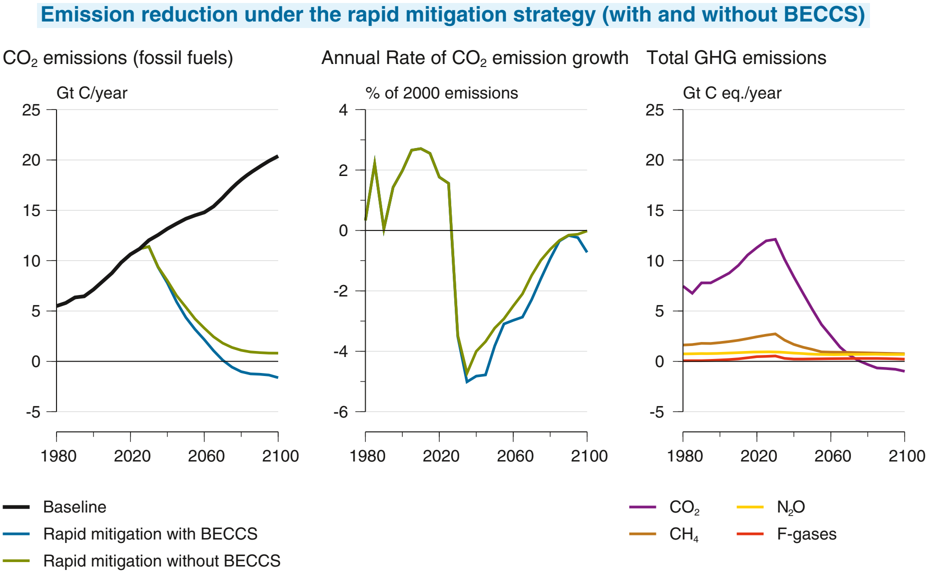

Fig. 2 Fossil-fuel related CO_2 emissions (GtC) (*left*), annual emission reduction (*middle*) and total greenhouse gas emissions (*right*) in the rapid mitigation scenario (*left* and *middle* panel show scenario runs with and without BECCS (Bioenergy and carbon-capture and storage); the *right* panel shows only the scenario with BECCS included)

reduction rates, accounting for delays in governance structures and societal structure or financial constraints could result in slower rates (see also discussion section).

Obviously, also the reduction of CO_2 emissions from land use and non-CO_2 gases could play a role in this discussion. To some degree, reduction of non-CO_2 gases may be achieved more easily than CO_2 from energy (e.g., reducing methane emissions from energy production), but in many cases only a limited amount of abatement options has as yet been identified (Lucas et al. 2007). Recent literature on the reduction of short-lived climate forcers (methane, ozone and black-carbon) indicates that rapid climate benefits can be achieved by reducing these gases (UNEP, WMO 2011). In the calculations presented here, we have included implicit reduction measures for methane (consistent with the carbon price) and only indirect reductions for ozone and black carbon as result of changes in the energy system. This, in fact, implies that the emissions of these gases are significantly reduced: for instance, methane emissions are assumed to be reduced within 20 years from 3.1 to 1.3 GtC (Fig. 2). N_2O emission reductions, in contrast, are much more bounded as a result of limited available technical emission reduction options (Lucas et al. 2007). The CO_2 emissions from land use are reduced at a somewhat slower rate, which is partly due to an increase in land claims as a result of bio-energy expansion. In the literature, some scenarios show a very rapid expansion of forests (Wise et al. 2009), but one may seriously question whether real world limitations (such soil quality) are consistent with those results.

3 Solar radiaton management

Various forms of 'geoengineering' have been proposed to reduce the impacts of climate change (The Royal Society 2009). There are two main categories: 1) removal of CO_2 from the atmosphere (CDR), and 2) solar radiation management (SRM). The first category includes measures such as iron fertilisation of oceans and direct capture of CO_2 from the air. For many CDR options, the impact is not very different from measures that are already often considered as part of mitigation strategies, such as reforestation and BECCS (although the option of negative emissions will influence the overall timing of emission reductions). Several CDR options are currently assessed as relatively expensive (The Royal Society 2009). The second category, SRM, might be an attractive rapid response option (Keith et al. 2010). One SRM option is the introduction of sulphur aerosols in the stratosphere, which would reduce radiative forcing by scattering incoming radiation (Crutzen 2006; Schneider 2008) (from now on, we refer to this option using the term SRM). The lifetime of sulphur aerosols in the stratosphere is 1 to 2 years, i.e. long enough for the aerosols to be effective, but at the same time short enough to be regarded as reversible. As a result of the effective radiation scattering of aerosols in the troposphere, the amount of sulphur aerosols needed is only a fraction of current anthropogenic sulphur emissions (The Royal Society 2009). An important feature is that, in principle, SRM can be scaled up from a small reduction in radiative forcing up to several Watts per m^2. The costs of large-scale application of this option are estimated to be only in the order of 10s of billion USD per year (Bles 2009), i.e. much lower than the costs estimated for mitigation strategies. Several modeling studies have suggested that injecting sulphur into the stratosphere can be very effective (Caldeira and Wood 2008; Matthews and Caldeira 2007; Wigley 2006), but possible side effects are still unknown. For instance, the impact of 'sulphur cooling' on different climate parameters (e.g., temperature, precipitation) may not be equally distributed around the planet and, therefore, could lead to disturbance of (local) climate systems (Keith et al. 2010; The Royal Society 2009). There also may be unwanted side effects, such as reduced precipitation and evaporation levels, stratospheric ozone depletion, and ecosystem alterations (Keith et al. 2010; Robock et al. 2008; The Royal Society 2009). The impact of these side effects could be worse than the avoided impacts of climate change. As such, the low costs need to be evaluated against the additional risks, see also Goes et al. (2011).

In terms of response time, there are important differences between SRM and mitigation. In a technical sense, the introduction of SRM, once established as a technique, could be more or less immediate. Making SRM techniques operational, however, is likely to take considerably more time. Assuming that society will choose to carefully learn about possible side effects, the time needed for modeling studies and small scale experiments could be in the order of decades (Keith et al. 2010). Governance issues could also involve time. At the moment, governance structures for applying SRM options are mostly lacking, except for the restrictions in the context of the Convention on Biodiversity. Several authors have called for the development of more official structures, which may be important even if society decides against using SRM (Barrett 2008; Schneider 2008; Victor 2008).

Here, we assume that society decides to invest into technology learning and building-up governance structures for SRM leading to a situation in which SRM could directly applied in 2030. In that case, its effectiveness is only bounded by the characteristics of the climatic response times. To explore these response times, we here assume two scenarios in which SRM is introduced in 2030 to reach to two radiative forcing levels: 2 W/m^2 and 3.5 W/m^2 which would be achieved immediately (if SRM could only be introduced gradually, the response time would obviously be delayed accordingly). As GHG concentrations would continue to rise, the required intensity of the SRM measure would increase over time. So-far, most authors have actually argued that SRM should at best be considered an additional measure to mitigation, either to allow for slightly less rapid mitigation rates or to avoid detrimental impacts of scenarios with high climate sensitivity (The Royal Society 2009; Wigley 2006).

4 Results for climate parameters

4.1 Response times of different strategies

Figure 3 shows emissions, radiative forcing, temperature and sea-level rise under the rapid mitigation and SRM strategy. While the rapid mitigation scenario leads to an immediate decrease in emissions in 2030, radiative forcing still continues to increase for about 10 years and only start to significantly decline 15 to 20 years after the peak in emissions reaching a level of 2.9 W/m^2 by the end of the century. The temperature profile shows further delay, due to inertia in the climate system. For the assumed climate sensitivity, global mean temperature increases to about 1.8 °C above pre-industrial levels by 2030. The rapid mitigation scenario limits further increase to 0.4 °C, but this peak is only reached by 2060, i.e. 30 years after the moment the policy was introduced. One of the factors leading to delay is that associated decline of sulphur emissions (from fossil-fuel combustion) reducing its cooling impact (Van Vuuren et al. 2007; Wigley 1991). The 2100 temperature is projected to be 2.1 °C above pre-industrial levels; in other words, after 70 years temperature is still 0.3 to 0.4 °C degrees higher than at the moment the policy was introduced. Slower processes, such as sea level rise, would even continue until the end of the century.

In the calculations, the reduction in radiative forcing and temperature increase is obviously limited by the emission reduction rate, but also by the slow processes involved in the removal of CO_2 from the atmosphere. Although the mitigation strategy partly depends on active removal of CO_2 from the atmosphere (negative emissions from BECCS), the results show that the system will be locked in with a relatively high GHG concentration for a long time. For temperature, a further delay occurs due to the slow heat release by the oceans. The slowness of these processes could be very relevant if additional feedbacks would be induced.

While the impact of SRM on radiative forcing is direct, still some delays occur in the climate signal. We explore two different strategies. In the first (A) we assume that action freezes radiative forcing at its 2030 level (3.6 W/m^2). This initially results in a similar temperature increase as in the rapid mitigation scenario, determined by climate inertia. In the long run, however, the rapid mitigation case performs better than this SRM strategy, as the continued emission reductions leads to decreasing radiative forcing. In a second SRM scenario (B), we assume immediate reduction radiative forcing to only 2 W/m^2), however, leads to an immediate response in global temperature, decreasing to around 1.3 °C above pre-industrial levels, in just 10 to 15 years[2]. Subsequently, temperatures are projected to remain more or less at this level. Sea level rise, in contrast, are projected to continue to increase due to its slow response time.

4.2 Other risks associated with SRM stategies

The discussion above clearly shows that in terms of response times, the stringent SRM strategy could have an advantage above mitigation strategies. There are, however, important risks associated with SRM as discussed in the literature. Here, we will briefly discuss them in the context of the scenarios presented in this paper. The first risk is that SRM strategies do not prevent the increase in CO_2 concentration and ocean acidity (as pointed out earlier by e.g., Robock (2008)). This can be shown for our illustrative scenarios by calculating the ocean acidity using a very simple correlation with atmospheric CO_2 concentration. This relationship suggests that both SRM options lead to a decrease in ocean pH from the current

[2] Note that we implemented the strategy rather rapidly for illustration purposes, if a sudden drop in temperature would be considered dangerous by itself, the strategy could also be implemented more smoothly

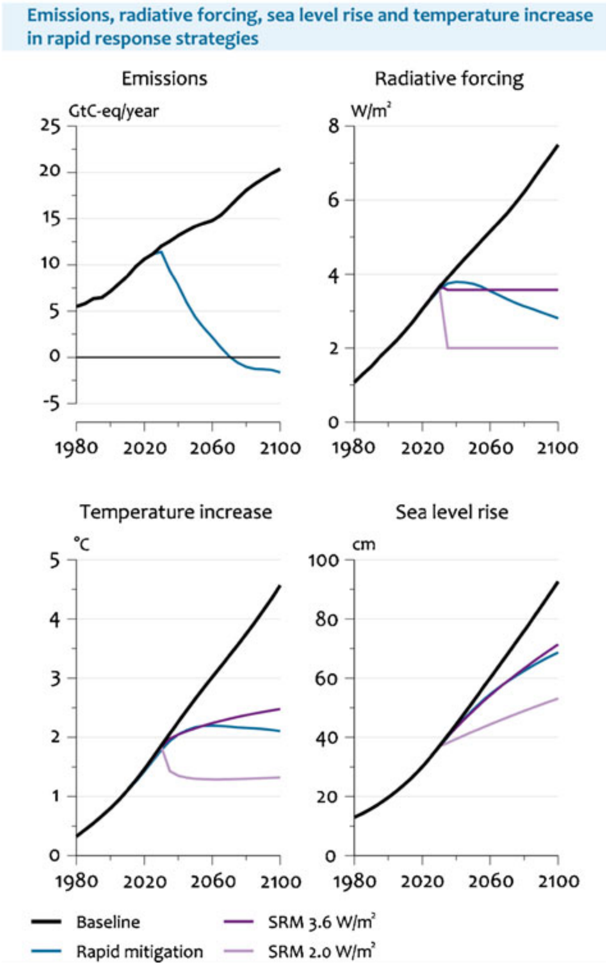

Fig. 3 Greenhouse gas emissions, radiative forcing, global mean temperature increase above pre-industrial levels and sea level rise in the rapid response scenarios (SRM = Solar Radiation Management; rapid mitigation includes BECCS)

8.1 to 7.8 by 2100 and continue to decline afterwards[3]. This decline is mostly prevented under the rapid mitigation strategy. While a full account of the ecological consequences of a decline in ocean pH is still uncertain, it appears likely that many calcifying species could be adversely affected (Adams and Caldeira 2008; Caldeira and Wickett 2003; Orr et al. 2005).

Another implication of SRM is that action will need to be continued and increased forever unless it is accompanied with mitigation. Clearly, there are many other actions that human

[3] We estimated the ocean acidification based on a simple off-line calculation calibrated to numbers found in the literature for 2100 atmospheric CO_2 concentration and the pH of the upper ocean layer to derive the following relationship: $pH_{ocean} = 10.498 * CO_{2,atm}^{-0.0443}$ (Adams and Caldeira (2008) Ocean storage of CO2. Elements 4:319–324, Caldeira and Wickett (2003) Oceanography: anthropogenic carbon and ocean pH. Nature 425:365, Orr et al. (2005) Anthropogenic ocean acidification over the 21st century and its impact on calcifying organisms. Ibid. 437:681–686.)

societies need to do forever in order to sustain (e.g. fertilizer production to produce food for 9 billion people), but with SRM this is combined with unknown risks. If such risks (e.g. unwanted change in weather patterns) would force humans to reconsider the SRM action, the lock-in dynamic could become very important. We illustrate this by implementing SRM scenario B (2 W/m^2) in which SRM is ceased again by 2060 (Fig. 4) (see also Goes et al. (2011)). This leads to extremely fast climate change, with radiative forcing jumping back to the value consistent with the atmospheric GHG concentration. This lead to a return to the original baseline situation in just a few decades, resulting in an extreme jump in temperature of more than 1 °C in just 5 years (Fig. 4). The results of the simple climate model MAGICC presented here are similar to those calculated by more complex models for slightly different cases (Brovkin et al. 2009; Matthews and Caldeira 2007). The risks involved in discontinuing SRM imply that in the choice of SRM versus rapid mitigation responses many other risks also have to be accounted for, including even those related to governance.

5 Discussion and conclusions

This paper has shown that the response time of different climate strategies is a critical parameter determining the timing of effective policy-making. We have assessed the typical response times for two contrasting climate policy strategies and the associated consequences. It is important to note, however, that little information is available, and while inherent uncertainties exists, further research in this area seems useful.

5.1 Maximum emission reduction rates and its implications

In Section 2, we discussed factors that determine the maximum emission reduction rate and indicated that these rates in current scenario literature range from 4 % to 6 % (among others depending on the period covered). More rapid reductions might be possible, if other drastic changes are introduced such as lifestyle changes including dietary change (Stehfest et al. 2009), premature capital replacement, drastic reforestation or a further deliberate focus on short-lived climate forcers (UNEP, WMO 2011). It should be noted, however, that some of these measures have already been (partly) accounted for in the literature and based on historical experience, one may question whether these rapid reduction rates could be achieved (see Section 2). To explore the influence of the uncertainty in the emission reduction rate, we have conducted an additional analysis in which we vary the long-term reduction rates from 2 % to 6 % (Fig. 1 shows that this covers most of the relevant reduction rates in the literature). For this, we developed a set of exogenous CO_2 emission profiles in which we assume that the long-term reduction rates can be sustained for the full period after 2030 until a negative emissions is reached of −2 GtC per year for energy/process related CO_2 emissions (Fig. 5). Emissions of other GHGs and air pollutants have been scaled based on their correlation with energy-related CO_2 emissions in existing IMAGE scenarios. The floor of −2 GtC is similar to the value reached in the lowest scenario for IPCC assessments. For a 2 % reduction rate, CO_2 emissions are even in 2100 not reduced to zero; a 3 % reduction rate implies that emissions are reduced to zero in about 55–60 years, while a 6 % reduction rate, reduces CO_2 emissions to zero in only 25–30 years.

The results show that in the 2 % reduction rate case, radiative forcing is only stabilized around 2050 and temperature will continue to increase throughout the century. The most ambitious case of a 6 % reduction rate leads to a peak in radiative forcing in 2040 and following by a steady decline back to 2010 radiative forcing levels in 2100 (2.6 W/m^2). In terms of temperature, however, even this very extreme assumption leads after 70 years to a global mean temperature that is still above

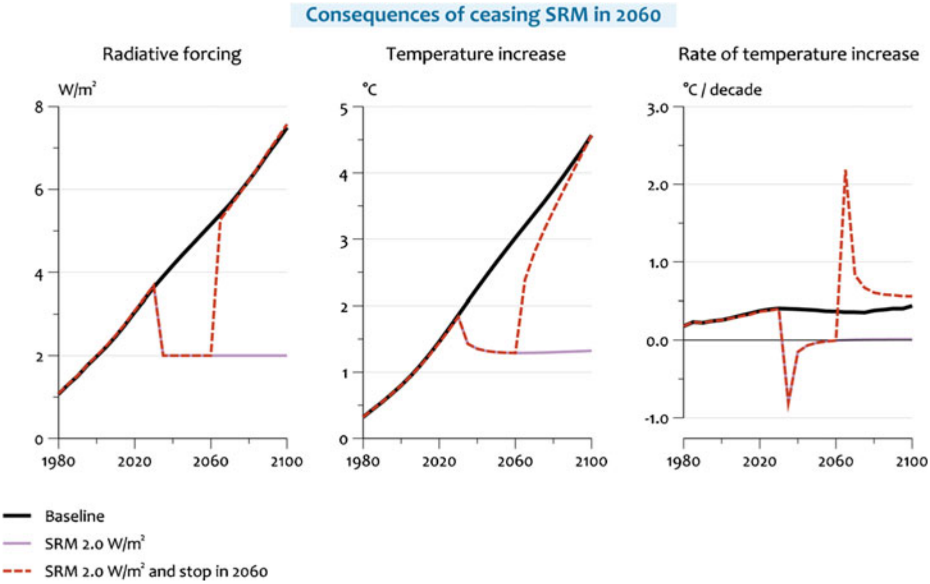

Fig. 4 Radiative forcing (*left*), global mean temperature increase above pre-industrial levels (*middle*), and rate of temperature change(*right* panel) in the SRM-scenario, including a variant in which SRM is ceased in 2060 (SRM = Solar Radiation Management)

the temperature level in 2030 when the policy is introduced (for the climate sensitivity of 4.5° applied here). None of the scenarios is able to reverse the trend for sea-level rise. In other words, response times are clearly very important in the case of (delayed) mitigation strategies.

6 Main conclusions

The following main conclusions can be drawn.

Response times play a critical role in deciding on attractive climate policy strategies, certainly in a situation of delayed action. So-far, most of the literature has focused on climate policies that consider gradually increasing (optimal) effort over time. In reality, however, there are several reasons why in the near-term climate policies are implemented much slower than these optimal pathways. In these delayed action situations, it might be important to respond rapidly if climate change would "suddenly" be more severe. Response times are critical in this debate. The importance of inertia can be illustrated by looking at the rates at which systems changed in the past: e.g. it took oil and gas 5 decades to increase their market share from 10 to 60 %. It should be noted that the response times presented in this article, and in particular the limits to the rate of mitigation, are still very uncertain and this is an important area for future work.

While mitigation can effectively reduce climate change, there are considerable response times involved (of several decades at least). In contrast, an SRM strategy might directly reduce radiative forcing, but this would significantly depend on the stringency with which the measure would be introduced. The results show that a rapid mitigation scenarios, i.e. a scenario equivalent to the high-end of the literature range in terms of reduction rates, could

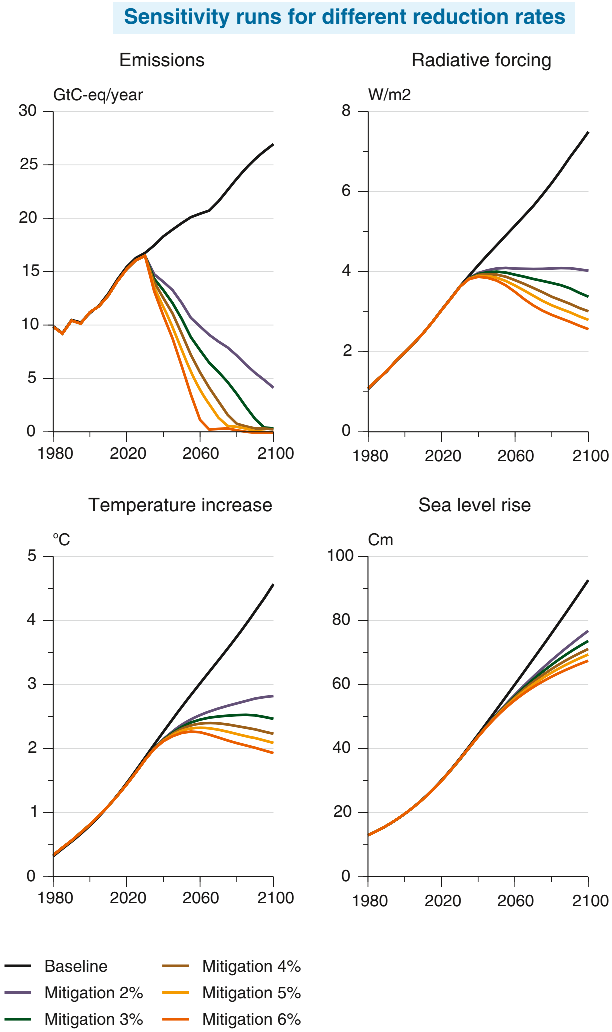

Fig. 5 *Greenhouse gas emissions, r*adiative forcing, global mean temperature increase above pre-industrial levels and sea level rise: sensitivity runs exploring reduction rates of energy/process-related CO_2 of 2–6 % (assuming a floor of −2 GtC/per year). Other emissions have been coupled on the basis of correlation in existing scenarios, except for CO_2 emissions from land-use for which the results of the mitigation scenario presented in Fig. 3 has been used

effectively limit further temperature increase to less than half a degree after its introduction. For this, however, we assume a decarbonisation rate that would require an immediate shift towards non- or low-CO_2 emitting technologies only bounded by the capital turn-over rate. The peak in temperature, however, would not occur until around 30 years after the introduction of the policy, and even after 70 years temperature would still not have returned to the level in the year of introduction. A SRM strategy that would only "freeze" forcing would not do much better than the rapid mitigation strategy, but could potentially be attractive in combination with mitigation. The more ambitious SRM strategy that would reduce radiative forcing back to 2000 levels would have more immediate results on global mean temperature change (but, for instance, sea level rise would even continue). Both SRM strategies, however, would leave the problem of ocean acidification unsolved and possibly bear significant risks. Even more, if not combined with mitigation, it would have to be continued forever, as the risks of stopping its application seem severe.

Further research on the implications of SRM, also as rapid response option, is needed. Calculations presented here and in other publications mostly show that it is not attractive to consider SRM as an alternative to mitigation given the risks involved. Still, the shorter response time provides an important attribute that may in some situations be attractive in combination with a stringent mitigation strategy (as argued e.g., by Wigley (2006) or Smith and Rasch (2012)), so that in the long term, SRM measures could be discontinued again. It is clear, however, that the current knowledge on SRM is still insufficient; further research on this is therefore needed. Finally, it should be noted that early mitigation might be a way to reduce the risk of sudden disruptive climate impacts that would need urgent response option and thus to avoid some of the limitations to the rapid response strategies described here.

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