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To what extent can a long-term temperature target guide near-term climate change commitments?

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Abstract The question of appropriate timing and stringency of future greenhouse gas (GHG) emission reductions remains an issue in the discussion of mitigation responses to the climate change problem. It has been argued that our near-term action should be guided by a long-term vision for the climate, possibly a long-term temperature target. In this paper, we review proposals for long-term climate targets to avoid 'dangerous' climate change. Using probability estimates of climate sensitivity from the literature, we then generate probabilistic emissions scenarios that satisfy temperature targets of 2.0, 2.5, and 3.0°C above pre-industrial levels with no overshoot. Our interest is in the implications of these targets on abatement requirements over the next 50 years. If we allow global industrial GHG emissions to peak in 2025 at 14 GtCeq, and wish to achieve a 2.0°C target with at least 50% certainty, we find that the low sensitivity estimate in the literature suggests our industrial emissions must fall to 9 GtCeq by 2050: equal to the level in 2000. However, the average literature sensitivity estimate suggests the level must be less than 2 GtCeq; and in the high sensitivity case, the target is simply unreachable unless we allow for overshoot. Our results suggest that in light of the uncertainty in our knowledge of the climate sensitivity, a long-term temperature target (such as the 2.0°C target proposed by the European Commission) can provide limited guidance to near-term mitigation requirements.

1 Introduction

The 1997 Kyoto Protocol, which entered into force 16 February 2005, is the first point of departure towards achieving the 1992 United Nations Framework Convention (UNFCCC 1992) Article 2 mandate of preventing "dangerous anthropogenic interference with the climate system" by distributing quantified emissions reductions commitments among developed country participants. Yet the rejection of the agreement by the US and Australia, and the absence of developing country commitments raises important questions about what

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a post-Kyoto climate regime may look like (see Aldy et al. 2003; Torvanger et al. 2004, among others).

An unresolved question is the appropriate stringency of abatement requirements. This is because there is great uncertainty with respect to both the costs of mitigation and expected climate change impacts. This has led some to argue that we should wait for more certain knowledge about the climate system before we take action, while others have argued that we should undertake modest near-term reductions to avoid expensive mitigation requirements in the future (Yohe et al. 2004). Whether we undertake early or delayed action, it has been suggested that in order to satisfy the UNFCCC Article 2 mandate, our near-term climate commitments should have an eye on long-term climate impacts. After all, "when starting a journey it makes sense to know where you are going" (Pershing and Tudela 2003). In essence, we should formulate short-term goals that are consistent with a long-term climate vision that satisfies the UNFCCC Article 2 goal. Consequently, a number of long-term climate targets have been proposed, including temperature targets such as that of the European Commission (EC 1996), limiting warming to 2°C above pre-industrial levels.

Given these proposals, and in light of the great uncertainties in the climate system, we ask: to what extent can a long-term climate target guide near-term mitigation commitments? We are interested in identifying the signals provided to climate policy for the next 50 years, particularly with regards to the appropriate timing and stringency of near-term reductions and the associated economic costs.

We approach the research question by generating abatement scenarios that meet specific long-term climate targets, and then seek to identify possible signals to near-term climate policy. Similar studies have been conducted in the past, through scenario generation (O'Neill and Oppenheimer 2002; Caldeira et al. 2003; den Elzen and Meinshausen 2005, 2006; Meinshausen et al. 2006) and the Tolerable Windows approach (i.e., Yohe and Toth 2000). However, this study takes a novel approach that employs probability estimates of climate sensitivity, and an integrated climate–economy model. In doing so, we generate 'probabilistic' estimates of near-term abatement requirements (and resulting costs) of achieving a long-term temperature target.

In the next section, we undertake a brief discussion and review of the literature on long-term temperature targets. In Section 3, we generate emissions scenarios for three possible long-term warming targets and the full range of climate sensitivities. In Section 4, we present the scenario results, in terms of allowable emissions and abatement costs. In Section 5, we conclude with a discussion of the policy implications of our results.

2 Long-term climate targets

In the current political discussions on climate agreements, the near-term perspective has received more attention than the long-term. This is arguably a result of the immediate (and often large) expected economic costs of near-term climate action, compared to the uncertain (and discounted) benefits of climate policy. The Kyoto Protocol was formulated without reference to a specific, quantified, long-term climate goal. Barring political feasibility issues, however, it is difficult to justify such a myopic approach when designing a climate strategy. Climate change is a problem that will likely have significant impacts for centuries to come. Because of historical greenhouse gas emissions, and the lag in the climate system, we are already committed to a certain degree of climate change (Hare and Meinshausen 2004; Wigley 2005). Furthermore, there is significant risk of dangerous impacts from anthropogenic climate change, and the frequency, intensity, and distribution of these impacts are expected to increase in the future (IPCC 2001a).

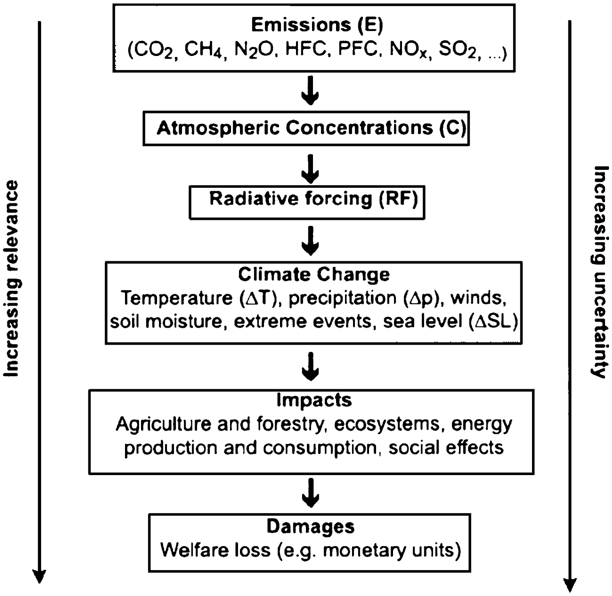
It has therefore been suggested that we should aim to incorporate a long-term vision of the climate into our near-term action. Ad hoc emissions reductions that are not framed by a long-term vision risk (a) doing too little, which may result in lost options of stabilization at specific levels and costly climate damage, or (b) doing too much, which may result in economic losses (Corfee-Morlot and Höhne 2003; Pershing and Tudela 2003; Tol and Yohe 2005).

Yet how should a long-term vision of the climate be defined? Of course, climate action (reducing emissions) is undertaken to avoid 'dangerous' climate impacts. However, climate policy is faced with two key issues: the uncertainty in the 'dangerous' climate impacts, and the cascading uncertainty along the causal chain of climate change. Related to the first issue, Article 2 does not indicate what climate impacts we should seek to avoid, or what levels would be considered 'dangerous.' Secondly, if we consider the causal chain of climate change (GHG emissions → radiative forcing → increased temperatures → climate change impacts → damage; see Fig. 1) and the cascading uncertainty along this chain, even if we are aware of the impacts we seek to avoid, we cannot know with any great certainty what emissions reductions would ensure we do so.

In spite of (or perhaps, a result of) these difficulties, it has been proposed that our long-term vision of the climate be a target defined in terms of a physical climate state (such as maximum temperature change), rather than specific 'dangerous' climate impacts. These physical climate states are precursors of the climate damage we seek to avoid (see Fig. 1), and thus form a bridge between our emissions reductions and the subsequent avoided damages.

Any choice of a specific climate target involves a compromise between the target's causal proximity and relevance to either (a) emissions or (b) the damages. To some extent, accessibility to understanding by the public is part of this compromise as well. This is

Fig. 1 Causal chain of climate change from emissions to damages. Source: Fuglestvedt et al. (2003)



reflected in the two main indicator types found in the literature: concentration targets (closely linked to emissions, but causally ‘distant’ to impacts), and temperature targets (linked closely to impacts, easily understood by the public, but causally ‘distant’ to particular emissions levels).

The long-term target proposals in the literature have a range of 1–4°C warming above pre-industrial levels, and concentrations of 450–700 ppm CO_2 (Oppenheimer and Petsonk 2006).[1] Below, we review a number of these proposals, dividing them into two camps: assessments based on either (a) historical climate states, or (b) expected climate impacts that would be considered dangerous.

2.1 Historical states

Looking to the past can possibly help us decide on what is acceptable for the future. The underlying principle in these studies is that we should seek to avoid climate change that exceeds the level of changes experienced in the past.

The Enquette Kommission (1991) defined an upper limit for the global temperature increase of 2°C (from pre-industrial levels) by 2100 such that mankind would not enter a climate regime it has never before experienced. The study also assigned a maximum rate of temperature change of 0.1°C per decade between 1980 and 2100 as the fastest pace at which natural ecosystems could adapt.

The German Advisory Council on Global Change (WBGU 1995) examined the temperature variation of the late Quaternary (the last 500,000 years). They suggested that moving outside the historical range of temperature change by 0.5°C would imply significant changes to today’s ecosystems. Their acceptable range corresponded to an average global surface temperature of 9.9–16.6°C. As the current global mean temperature is 15.3°C, we should thus limit future warming to 1.3°C. This corresponds roughly to a limit of a temperature increase of less than 2°C from pre-industrial levels. The council also recommended that the decadal rate of change should not exceed 0.2°C.

2.2 Expected impacts

The alternative, and more common, method is to identify climate impacts that should be avoided, and the climate change thresholds they are associated with. The United Nations Advisory Group on Greenhouse Gases (UNAGGG) proposed a number of long-term targets on the basis of maximum limits that were tolerable to both humans and ecosystems (Rijsberman and Swart 1990). The targets were expressed in terms of both maximum tolerable sea level rise and temperature increases (although they are not mutually exclusive):

- 20–50 cm sea level rise above 1990 level
- Sea level rise of 2–5 cm/decade
- 1–2°C temperature increase from pre-industrial levels
- 0.1–0.2°C/decade rate of temperature increase

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[1] It should be noted that there is variation in the literature as to how the climate states are referred. Some have proposed the levels as “targets” for climate policy (Rijsberman and Swart 1990; EC 1996), while others simply prescribe the climate levels as thresholds above which climate impacts would be deemed ‘dangerous.’ For simplicity, and the purposes of our scenarios in Section 3, we refer to all of these proposals as “targets.”

O'Neill and Oppenheimer (2002) used melting of the Western Arctic Ice Shelf (WAIS), coral reef destruction, and thermohaline circulation (THC) shutdown as indicators of dangerous climate change impacts. They suggested the following climate thresholds would avoid these impacts:

- A maximum increase of 1°C above 1990 global mean temperature would prevent severe reef damage.
- Temperature increases of less than 2°C above 1990 global mean temperature would protect the WAIS.[2]
- Temperature increases of less than 3°C within 100 years to avert THC shutdown.

Smith et al. (2001), Leemans and Eickhout (2004), and Hare (2003), identify local and global ecosystem impacts that would be considered 'dangerous' associated with a range of 1 to 2°C warming above pre-industrial levels.

A number of European governments have proposed similar targets:

The European Commission (1996) concluded that future carbon reductions should be "guided" by a target of limiting the CO_2 concentration to doubling from pre-industrial levels. More specifically, the EC goal was to stabilize the CO_2 concentration below 550 ppmv by 2050, and to limit the magnitude of warming to below a 2°C increase from pre-industrial times.

This goal was reaffirmed by Sweden (Klimatkommitén 2000) who proposed the stabilization of the six Kyoto greenhouse gases at 550 ppmv CO_2eq (500 ppmv CO_2 only) by 2050, citing "limited climatic impact" as the ultimate objective. The UK government (2003) cited an identical goal based in part on a report by the Royal Commission for Environmental Pollution stating that 550 ppmv was an "upper limit that should not be exceeded." The 2°C above pre-industrial target was reaffirmed by the EU in March 2005, with the associated concentration target revised to 550 ppmv CO_2eq for all greenhouse gases (EU Council 2005).

The weaknesses of such targets have been discussed in the literature, and it is unlikely that a specific target will ever be agreed upon in international negotiations. Firstly, while the backward-looking approach of the Section 2.1 grouping is an application of the precautionary principle, it may not be an appropriate one. The aim of climate action is not to prevent all change – only change that may be defined as "dangerous" (Tol 2001). Secondly, assigning targets from Section 2.2 is subject to great uncertainties, both in terms of the specific impacts we seek to avoid, and the climate states associated with them. Yohe and Toth (2000) argue that the targets are no more than "educated guesses." It has been suggested that even a 2°C warming is not likely to be truly safe with respect to dangerous climate impacts (Smith et al. 2001; Hare 2003; ACIA 2004).

Choosing a long-term vision (a specific target, or otherwise) for the climate is ultimately a normative task, and involves the opinions and values of the diverse people of the world (Schneider and Lane 2005). How should the expected impacts to future generations we seek to avoid be chosen and weighed? Tol and Yohe (2005) argue that attempting to reach agreement on an objective definition for 'dangerous' climate interference is futile – suggesting that agreeing upon a specific long-term target is also impossible. However, in spite of the uncertainties and difficulties in choosing a long-term target, in the next section we hypothesize that a single long-term target *can* be agreed upon, and assess the near-term implications of such a target by long-run emissions scenarios in the next section.

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[2] Given that warming in 1990 was roughly 0.5°C above pre-industrial levels, these two targets are thus 1.5, 2.5°C above pre-industrial levels, respectively.

3 Generating probabilistic emissions scenarios

We generate scenarios for three long-term climate goals: 2.0, 2.5, and 3.0°C above pre-industrial levels, with no overshoot[3] – given that overshooting may compromise the overall objective (Wigley 2003; O'Neill and Oppenheimer 2004). We choose these targets based on the range proposed in the literature.[4]

To generate emissions scenarios and assess the economic consequences, we iteratively employ both an economic and a climate model. The economic model is the model for Dynamic analysis of the Economics of Environmental Policy (DEEP) (Kallbekken 2004; used in Kallbekken and Westskog 2005). DEEP is a global, multi-sector, multi-region, multi-gas computable general equilibrium model, calibrated around the GTAP v5 database (Dimaranan and McDougall 2002). For this study, the model was set up for a single (world) region, and run for the period 1997–2100 in annual steps. We use economic growth and technological improvement factors from the SRES A1B scenario (IPCC 2000). The climate model is the CICERO simple climate model (SCM) (Fuglestvedt and Berntsen 1999; used in Fuglestvedt et al. 2003). The SCM incorporates a scheme for CO_2 from Joos et al. (1996) and an energy-balance climate/up-welling diffusion ocean model developed by Schlesinger et al. (1992). The climate model is run to 2250. Emissions from DEEP are extended beyond 2100 through extrapolation.

There exist an infinite number of long-term emissions scenarios that can satisfy a given temperature target. Thus, we make a number of standardizing assumptions in generating our scenarios. Firstly, abatement in each year is undertaken cost-effectively across the three main industrial GHGs: CO_2, N_2O, and CH_4 (using GWP-100 conversion), with an assumed discount rate is 5%. CO_2 emissions are modeled with a fixed factor composite of each primary energy input and CO_2 emissions permits (with constant CO_2 emissions per unit energy input). CO_2 abatement thus occurs through substitution away from the individual energy inputs. Non-CO_2 emissions are modeled in a fashion similar to the EPPA model (Hyman et al. 2003). Emissions permits of CH_4 and N_2O are direct inputs to the production function at the top level nest of the production structure. CH_4 and N_2O reduction occurs through substitution away from the emissions permits, leading to an increase in the use of all other inputs. Substitution elasticities are taken from Hyman et al. In the model, the emissions intensity of production falls over time in accordance with an assumed exogenous rate of technological improvement. See the Appendix and Kallbekken (2004) for further information, including the assumptions of non-industrial emissions and F-gases that do not appear in the DEEP model.

Secondly, it is assumed that society will optimize its mitigation strategy and equalize net present value (NPV) marginal abatement costs over time. That is, abatement costs will rise over time at the rate of interest. However, we do not allow this optimization to begin immediately. Rather, we assume the scenario undertakes a transition pathway from the start of abatement in 2010 (with the Kyoto Protocol) to the start of this optimality (after 2050).

Such a transition allows us to take into account constraints in the real-world which do not feature in DEEP, such as political feasibility and the costs of early capital retirement. We seek to ensure that the emissions scenario undertakes a near-term pathway that is "reasonable" in light of these constraints. Of course, what is "reasonable" is purely

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[3] The term 'overshoot' refers to when a scenario exceeds a given target (i.e., temperature) for a short period of time as a result of the climate system inertia, before eventually returning to the target level.

[4] We discard the lower limit of 1.0°C, given that we appear to be committed to this amount of warming regardless (Wigley 2005), as well as the upper limit of 4.0°C, as it is beyond the levels typically proposed.

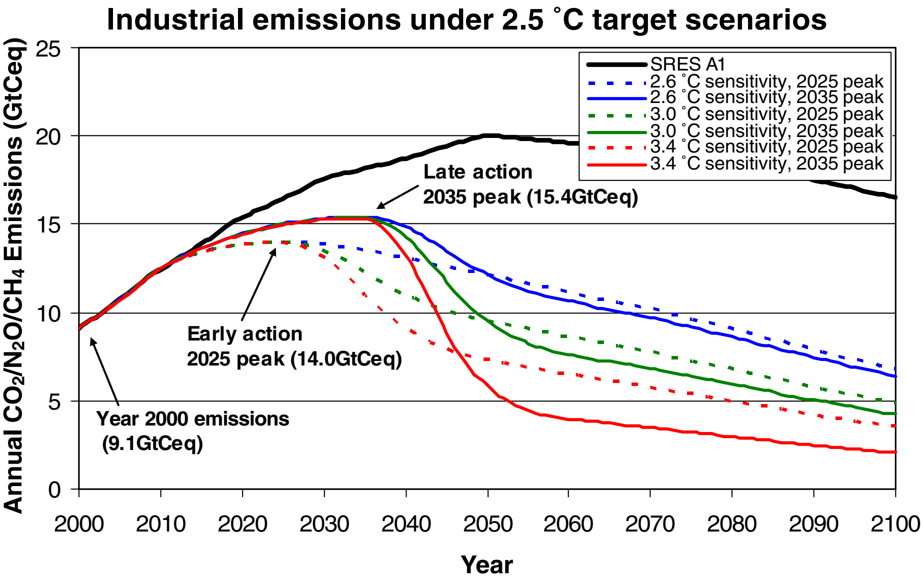

Fig. 2 Meeting a 2.5°C warming target under alternative climate sensitivities. A sensitivity of 3°C sensitivity is equal to the midpoint of the IPCC (2001b) uncertainty range, while 2.6 and 3.4°C are representative 'low' and 'high' levels

speculative, and thus we employ two alternative near-term transition pathways: the 'Early' and 'Late' climate action scenarios. The format of our scenarios is illustrated in emissions and permit price trajectories for selected climate sensitivities[5] in Figs. 2 and 3.

In our scenarios, mitigation action is started in 2010, at which point global emissions begin to deviate from the BAU. This is to represent the Kyoto Protocol, however for simplicity no specific global emissions level or regional participation (i.e., with or without the United States and Australia) is considered. The emissions in 2010 are dependent on the transition to peak emissions (see below). This is justifiable, as the global emissions level under the Kyoto Protocol is highly uncertain, and will have little impact on our results.

Industrial emission levels are assumed to peak in either 2025 (for the Early case) or 2035 (the Late case) at 14.0 GtCeq and 15.4 GtCeq, respectively (see Fig. 2). Optimal abatement is started in 2050 and 2060 for the Early and Late cases, respectively, from which point onwards the NPV permit price is constant (see Fig. 3). The transition between the peak level and start of optimality is constructed in DEEP with a simple geometric function.

Finally, we assume that once temperatures begin to retreat from the temperature targets, society will continue to engage in mitigation action at the optimal levels to further reduce temperatures (see temperature curves in Fig. 4). An alternative approach could seek long-term stabilization at the target temperatures, which would allow for higher emissions levels in the long-term compared to those seen in our scenarios (Fig. 2). However, there would be no impact on our results, as the stabilization only occurs in the distant future – beyond

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[5] Climate sensitivity refers to the equilibrium global mean temperature resulting from a doubling of CO_2 concentrations.

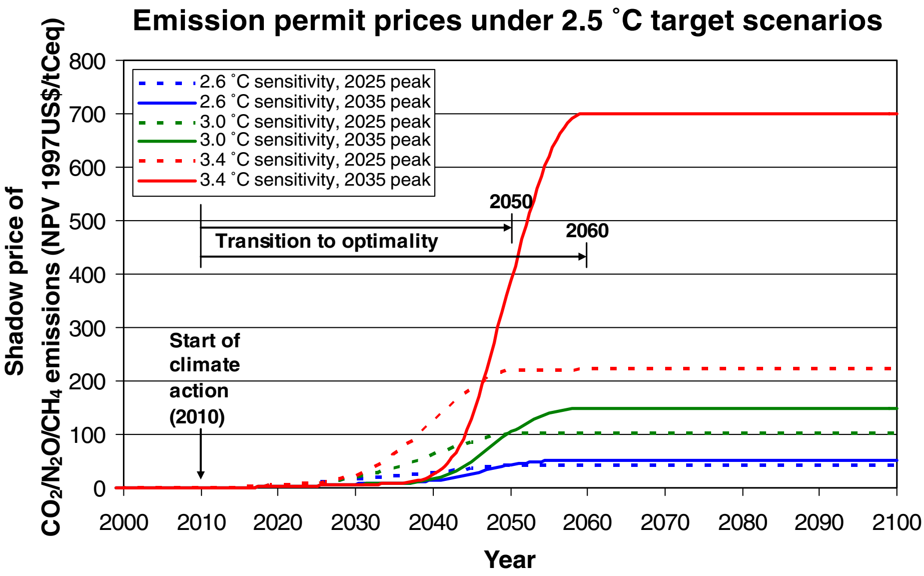

Fig. 3 Permit prices for industrial CO_2, N_2O, and CH_4 under the scenarios shown in Fig. 2

the near-term horizon we are concerned with in this paper. See the Annex for a discussion and illustration of background emissions assumptions and model parameters.

To account for the uncertainty in climate sensitivity, we take a generalized approach that employs probability estimates of climate sensitivity from the literature. We generate scenarios across all climate sensitivities, and present our results against climate sensitivity

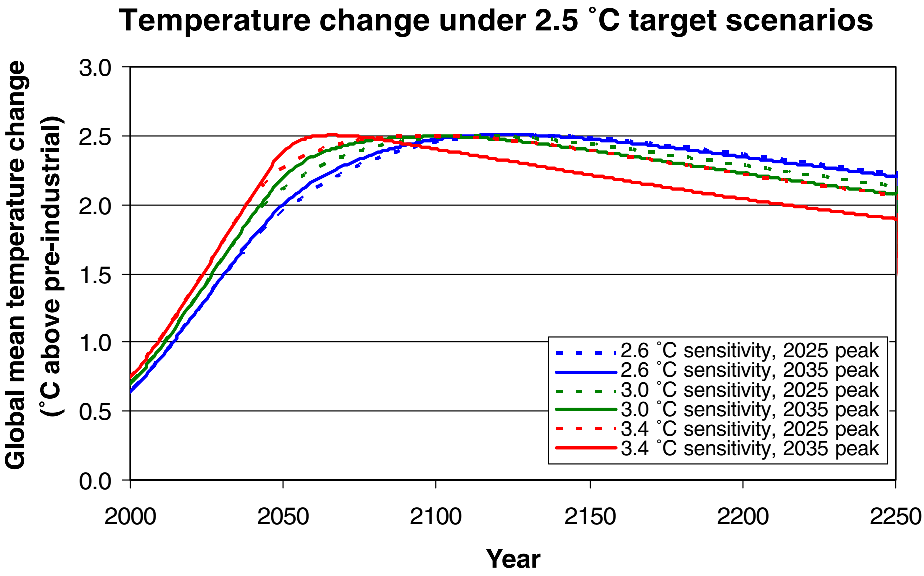

Fig. 4 Global mean temperature change under scenarios shown in Fig. 2

probability ranges. This provides a better context for analysis and comparison than using representative “low,” “medium,” and “high” climate sensitivities. A similar approach has been seen in the literature both with an economic model (Mastrandrea and Schneider 2004; den Elzen and Meinshausen 2005) and without (O’Neill and Oppenheimer 2004; Meinshausen 2006; Wigley 2005; Knutti et al. 2006). Our results contribute to this literature by focusing on the implications of a temperature target on near-term abatement requirements.

Our climate sensitivity probability estimates come from a set of 10 studies in the literature (Fig. 5). In comparing these estimates with our emission scenarios, we use three key lines. The first, colored blue in the figure, is the average (mean) probability for each climate sensitivity across the 10 studies. This is equivalent to adding up the 10 respective probability density functions (PDFs), and generating a new normalized cumulative density function (CDF). While this average can be interpreted to represent the best estimate for our knowledge of the climate sensitivity, the large range of probability estimates must still be highlighted. This is done with the orange lines in Fig. 5, which illustrate the upper and lower bounds of the literature estimate. The orange lines are labeled as the ‘high’ and ‘low’ climate sensitivity estimates, referring to their respective estimates at the 50% cumulative probability level.

4 Allowable emissions and costs

In this section, the results of our scenarios are presented. The first set of results (Fig. 6) are the probabilistic abatement requirements in achieving the temperature targets of 2.0, 2.5, and 3.0°C above pre-industrial levels. The figure shows what industrial emissions levels are required in 2050 (in the Early action case) and 2060 (Late action) if we are to achieve the

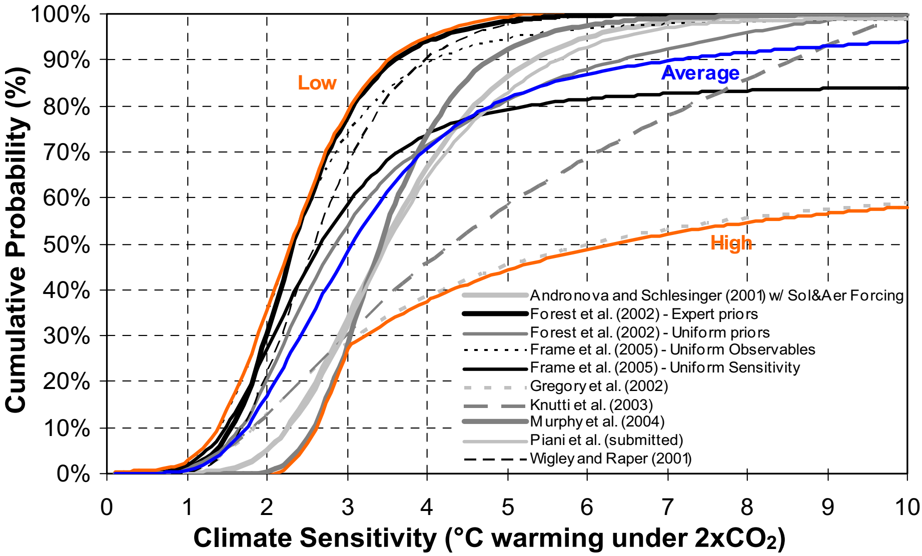

Fig. 5 Cumulative density functions of climate sensitivity estimates. Data compiled by Meinshausen (2006). *Orange lines* denote low and high climate sensitivity estimates in the literature, while the *blue line* denotes the average

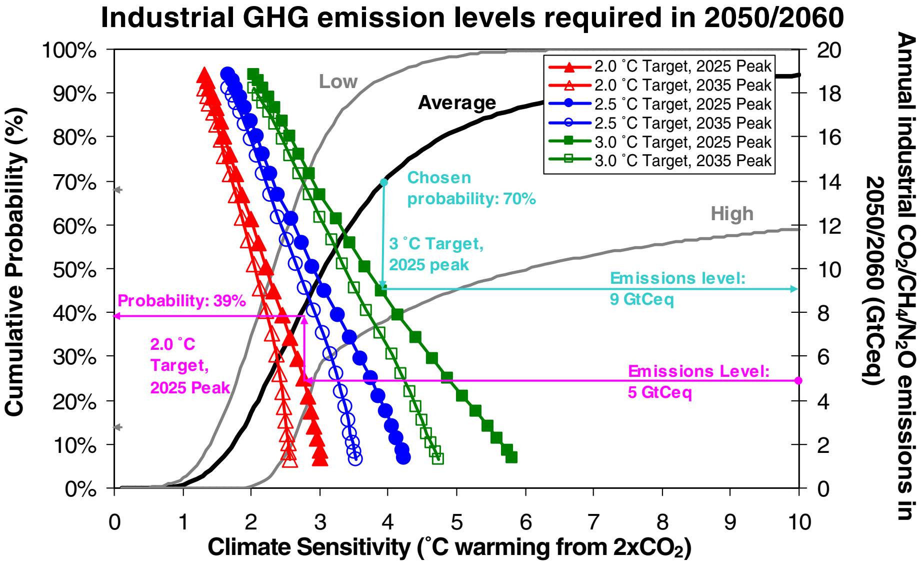

Fig. 6 Probabilistic estimates (*black/grey curves*, *left axis*) of required emissions levels in 2050/2060 (*colored curves*, *right axis*) to meet 2.0, 2.5, and 3.0°C warming targets. Probability curves denote the low, average, and high climate sensitivity probability estimates from the literature

respective climate targets. The years 2050 and 2060 are used as proxy years to present the results, as a time series chart is not possible. Figure 6 overlays the abatement requirements for the six temperature target and Early/Late case combinations (the red, blue, and green curves; read against right *y*-axis) on top of the Low, Average, and High climate sensitivity estimates from the literature (grey and black curves; read against the left *y*-axis).

Figure 6 can be read in two ways. Firstly, it can indicate the likelihood of achieving a specific temperature target given the achievement of certain level of emission reduction in the near-term. Such an example is demonstrated in the figure (pink-colored arrows). It can be seen that if the Early action scenario achieves a global industrial GHG level of 5 GtCeq in 2050, it is on track to achieve the 2°C temperature target with 39% probability (average estimate).

Alternatively, the figure can indicate the required level of abatement to achieve a given target with a desired probability. Such an example is demonstrated in the figure in aqua-colored lines. It is seen that to achieve a 3°C temperature target under Early action with 70% confidence, industrial GHG emissions much fall to at least 9 GtCeq in 2050, roughly equal to the level in 2000.

It should be noted that we have included the low and high sensitivity curves from the literature to highlight the range of probability estimates and the implication on the reduction requirements (Fig. 6). Using the example in which emissions reach 5 GtCeq in 2050 (pink arrows), we see that while the average probability estimate for achieving a 2°C target is 39%, the probability is 67% in the low sensitivity estimate, and only 14% in the high case (grey arrows).

The abatement costs that correspond to the emissions scenarios in Fig. 6 are presented in Figs. 7 and 8. Generated in the DEEP model, these costs are the NPV marginal abatement costs (i.e., permit price) in 2050 and 2060 in the Early and Late action scenarios, respectively. These years are the first years in which optimal abatement is undertaken, and

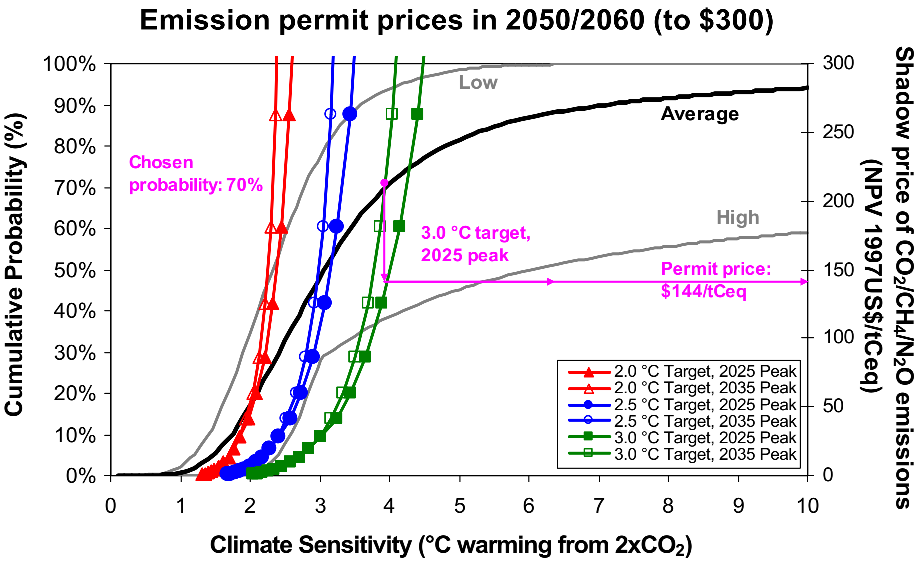

Fig. 7 Probabilistic estimate (*black/grey curves*, *left axis*) of abatement costs per ton carbon equivalent at optimality (*colored curves*, *right axis*) to meet 2.0, 2.5, and 3.0°C warming targets. The right hand axis is limited to $300/tCeq for clarity. At $300/tCeq, global industrial GHG emissions in 2050/2060 are at approximately 5.5 GtCeq

thus the NPV marginal abatement costs are constant from this point onwards. For clarity, we have presented the costs in two figures, although they are constructed from identical data. In Fig. 7, the lower range of costs (to $300/tCeq) are shown. Figure 8 illustrates the results for the full cost range calculated in DEEP (to $5,300/tCeq) in a logarithmic scale. Of course, the upper level of these costs are unlikely to be politically feasible in the real-world, and would likely be accompanied with rapid technological developments that do not feature in DEEP. However, we include them for a complete comparison with the GHG reduction requirements.

The cost curves can be read in a similar fashion as the GHG level curves. An example is highlighted in Figs. 7 and 8 (pink-colored arrows). It is seen that to achieve a 3.0°C warming target with Early action with 70% probability, the average literature estimate of climate sensitivity indicates this is associated with an abatement cost of $144/tCeq.

The costs of the emissions scenarios can also be reported in terms of total abatement cost, as a percentage of annual GDP (Fig. 9). In the figure, we display the results only to a total global abatement cost of 3% of GDP for clarity. This corresponds to a NPV permit price of roughly $400 t/Ceq in 2050/2060. A sample set of results is shown in Fig. 9 (pink-colored arrows): achieving a 3.0°C target with Early action with at least 70% confidence will be associated with global abatement costs equal to 0.8% of GDP in 2050. This corresponds to the $144/tCeq permit price and 9 GtCeq GHG limit shown in Figs. 6 and 7.

In the tables, we present notable results from our scenarios. Tables 1 and 2 indicate the allowable emissions levels in 2050 and 2060 (and associated marginal abatement costs) that achieve the European Commission target of limiting warming to 2°C above pre-industrial levels with 25, 50, and 75% confidence. Tables 3 and 4 indicate the probabilities of achieving temperature targets of 2.0, 2.5, and 3.0°C under Early and Late action, given that annual GHG emissions in 2050 and 2060 are returned to year 2000 levels (9.1 GtCeq).

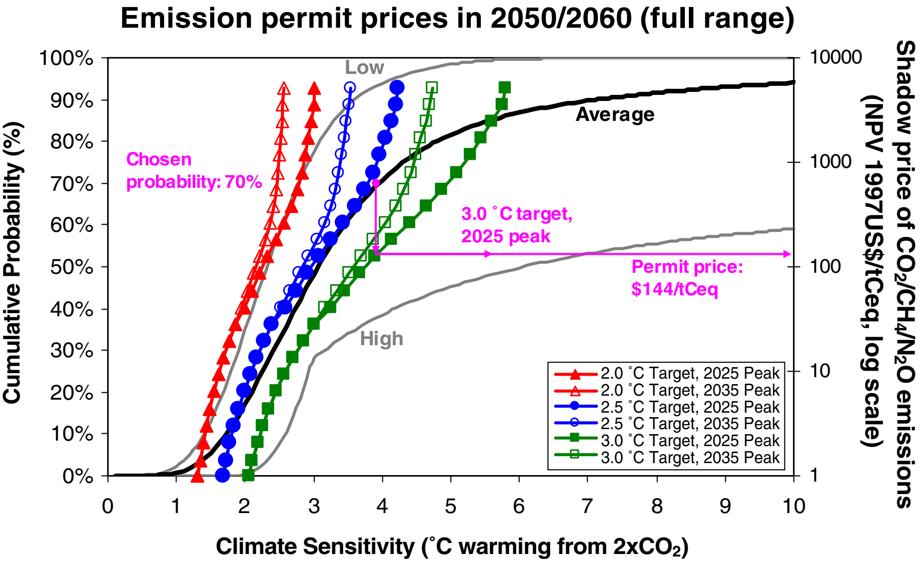

Fig. 8 Probabilistic estimate (*black/grey curves*, *left axis*) of abatement costs per ton carbon equivalent at optimality (*colored curves*, log scale *right axis*) to meet 2.0, 2.5, and 3.0°C warming targets

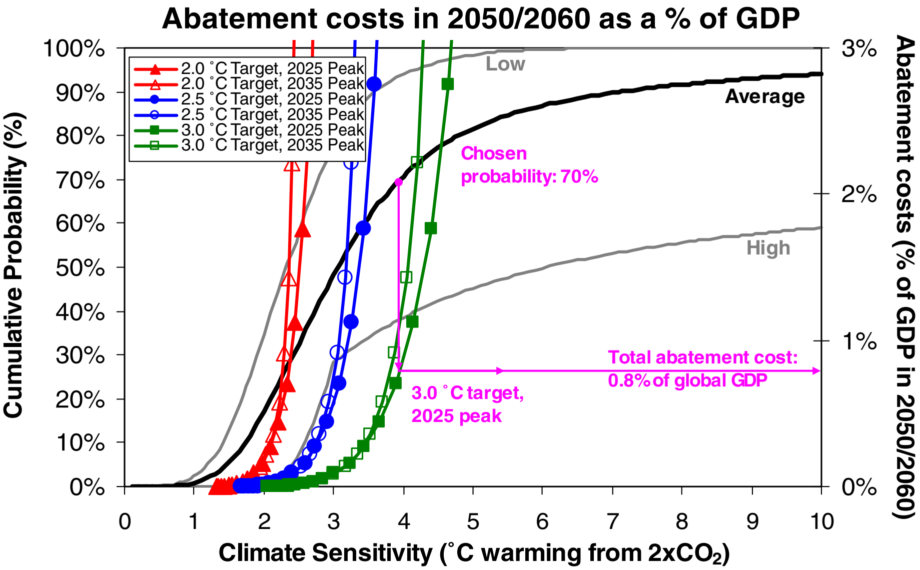

Fig. 9 Probabilistic estimate (*black/grey curves*, *left axis*) of abatement costs as a share of GDP (*colored curves*, *right axis*) in 2050 (early case) and 2060 (late case) to meet 2.0, 2.5, and 3.0°C warming targets. A cost of 3% of GDP corresponds roughly to a permit price of $400/tCeq

Table 1 Industrial GHG emission levels in 2050 (in GtCeq) that achieve a 2°C warming target under early action (2025 peak emissions), and associated global NPV permit price (1997$US/tCeq)

Probability of achieving 2°C target (%)	Low estimate	Average estimate	High estimate
75	3 GtCeq ($1400/tCeq)	N.A.	N.A.
50	9.1 GtCeq ($130/tCeq)	1.8 GtCeq ($3500/tCeq)	N.A.
25	14.5 GtCeq ($20/tCeq)	10 GtCeq ($90/tCeq)	1.8 GtCeq ($3500/tCeq)

First column denotes cumulative probability of achieving the target under the low, average, and high estimates from the literature. N.A. indicates that achieving the target is not achievable without overshoot. Year 2000 emissions were 9.1 GtCeq.

5 Conclusions

Our scenarios assume that a long-term temperature target can be agreed upon in future climate negotiations, and highlight the implications of such a target for mitigation policy in the near-term. While it has been argued that setting a temperature target is an appropriate way of adopting a long-term vision in near-term climate agreements, agreeing upon a specific target may be difficult, and so far only the EU has adopted an official target. Regardless, our results suggest that under the current state of knowledge of the uncertainty of climate sensitivity, a long-term temperature target provides only ambiguous signals to near-term climate policy. This is manifested in two ways:

The 90% confidence interval of climate sensitivity estimates exhibits a wide range of possible sensitivities, and consequently identifies a wide range of near-term emissions levels that are consistent with a given temperature target. Combining the literature estimates into a single, average CDF (Fig. 5) yields a 90% confidence interval of climate sensitivity estimates of 1.4 to 7.2°C. Achieving a 2°C warming target under Early action with 1.4°C climate sensitivity allows an emissions level in 2050 of 18 GtCeq, while a climate sensitivity of 7.2°C makes it impossible to reach. The breadth of this interval means that when developing abatement strategies for preferred levels of risk aversion (i.e., a chosen confidence level), marginal changes in risk aversion will yield large changes in near-term abatement requirements.

The probability estimates across the literature are wide-ranging, particularly for higher climate sensitivities. While it is possible to combine the sensitivity estimates in the literature into one average CDF as a meta-analysis, it may be appropriate to also consider the range of sensitivity estimates in the literature. The range highlights the differences in the methodologies found in the literature, and indicates the width of uncertainty of the probability estimates. As shown in Table 1, the acceptable emissions level in 2050 (early action) that satisfies a 2°C target with 50% certainty ranges from 9 GtCeq, to 2 GtCeq, to

Table 2 Industrial emission levels in 2060 (as a % of year 2000 levels) that achieve a 2°C warming target under late action (2035 peak emissions), and associated global NPV permit price (1997$US/tCeq)

Probability of achieving 2°C target (%)	Low estimate	Average estimate	High estimate
75	N.A.	N.A.	N.A.
50	7.3 GtCeq ($180/tCeq)	N.A.	N.A.
25	14.5 GtCeq ($20/tCeq)	9.1 GtCeq ($130/tCeq)	N.A.

N.A. indicates that achieving the target is not achievable without overshoot. Year 2000 emissions were 9.1 GtCeq.

Table 3 Cumulative probability (low, average, and high sensitivity estimates) of achieving respective long-term targets, under Early action (2025 peak emissions) and annual industrial GHG emissions reduced to 9.1 GtCeq in 2050

Long-term target (°C)	Low estimate (%)	Average estimate (%)	High estimate (%)
2.0	50	26	2
2.5	79	27	48
3.0	95	69	37

unreachable in the low, average, and high sensitivity estimates. The marginal abatement costs of the low and average estimate levels are $130/tCeq and $3,500/tCeq, respectively. Thus, the probability estimates across the literature for a given climate sensitivity yield wide ranges of abatement requirements and costs for a given temperature target.

These ambiguities highlight the uncertainty under which any climate policy decisions must be made, and underline the crux of the climate problem: the cascading uncertainty along the climate change causal chain (Fig. 1). Although it is beyond the scope of this paper to discuss the merits of particular climate targets, or indeed the use of any targets, our results suggest that setting a temperature target for climate policy does not unambiguously indicate levels of greenhouse gases we should aim to achieve in the near-term.

While our result is driven solely by the uncertainties in climate sensitivity, including the additional uncertainties that exist along the causal chain of climate change (Fig. 1) in our analysis would only serve to strengthen the conclusions. Of particular interest to this study are the uncertainties in radiative forcing (Boucher and Haywood 2004; Schwartz 2004), carbon-cycle feedbacks (Cox et al. 2000), and ocean-mixing, which would impact the causal chain between emissions and temperature change. Accounting only for climate sensitivity uncertainty is acceptable in this case, given that it is the dominant uncertainty in long-term temperature projections.

On the other hand, our results do indicate that the choice of timing can have serious implications for the cost and availability of long-term temperature targets. A delay of only 10 years may increase the cost of achieving a given target significantly, potentially putting it out of reach. For example, reaching a 2.5°C with 50% probability under Early action will cost $120/tCeq, whereas under Late action will cost $200/tCeq (Fig. 7). In Tables 1 and 2, we see that while a 2.0°C target may be achievable in certain instances under Early action, it may be unreachable under Late action. The impact of any delay is amplified at higher climate sensitivities, as the cost curves diverge (see Fig. 6).

It should be noted that using temperature targets in a deterministic fashion with no overshoot – albeit hypothetically – means that our scenarios are somewhat limited in their applicability to developing appropriate climate strategies. For instance, we do not (nor are we able to) to identify appropriate long-term climate goals in light of the risks, costs, and benefits of climate action. This would be embodied in a cost–benefit approach to the climate problem (see, among others, Nordhaus and Yang 1996; Tol 1997; Tol and Yohe 2005). However, our scenarios are useful in putting into perspective the official EU target and the other targets and thresholds proposed, in terms of their implications for near-term abatement requirements.

Alternative climate strategies have been discussed extensively in the literature. Beyond a strict cost–benefit approach, a hedging strategy may be an appropriate course of action to deal with the uncertainty (Manne and Richels 1997; IPCC 2001c; Pershing and Tudela 2003). Yohe et al. (2004) demonstrate that a low-cost hedging strategy (through the use of a carbon tax) can successfully keep significant long-term climate options open until we

Table 4 Cumulative probability (low, average, and high sensitivity estimates) of achieving respective long-term targets, under Late action (2035 peak emissions) and annual industrial GHG emissions reduced to 9.1 GtCeq in 2060

Long-term target (°C)	Low estimate (%)	Average estimate (%)	High estimate (%)
2.0	45	23	1
2.5	75	45	22
3.0	92	66	35

improve knowledge of our climate system, and reduce the costs of future reductions. Carbon taxes are effective in reducing the cost uncertainty of climate policy. O’Neill et al. (2006) consider the possibility of interim targets for climate agreements. Concentration targets may be a useful manifestation of a hedging strategy, given its causal proximity to emissions: our results suggest that temperature targets are a step too far along the causal chain to be effectively linked to emissions reductions.

If a hedging or cost–benefit strategy cannot be negotiated, future climate agreements may be limited simply by what can be feasibly agreed upon (Philibert et al. 2003). This feasibility will be based on a number of factors, including expected mitigation costs and benefits, public concern over climate change, participation among key actors, and burden sharing. Thus, a long-term target may only have partial influence on any near-term mitigation strategy. A third alternative is to implement a climate agreement that does not have emissions reductions as a core obligation. This includes agreements that focus on institution building and R&D in climate-friendly technologies, which may gain wider political acceptance and have longer-lived climate (and non-climate) benefits (Schmalensee 1996).

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Appendix

The structure of production and final demand in DEEP is based on the GTAP-E model by Rutherford and Paltsev (2000). Emissions of greenhouse gases are taken from Lee (2002, 2003). Economic growth and emissions intensity parameters are taken from the SRES A1B scenario (IPCC 2000).

The following assumptions are made for the background emissions of the gases not included in the DEEP model: SO_2 emissions from industrial sources are scaled using the industrial CO_2 emissions from the DEEP model as a proxy, using the SO_2:CO_2 ratio taken from the SRES A1B, which falls over time. CO_2 emissions from land use change follow the A1B scenario until 2030, after which it degenerates at a rate of 3% per year (year on year reduction). F-gases follow the A1B scenario until 2030, after which they fall at 5% per annum (year on year). CH_4, N_2O, and SO_2 from non-industrial sources (i.e., forest fires) also follow the SRES A1B scenario until 2030, after which they fall at 3% a year until they reach a minimum level of 50 Tg, 0.4 Tg-N, and 1.7 Tg-S, respectively; these are the assumed maximum reduction levels. Emissions from biomass burning are calculated using industrial SO_2 emissions as a proxy.

The CO_2 module in the SCM uses an ocean mixed-layer pulse response function that characterises the surface to deep ocean mixing in combination with a separate equation describing the air–sea exchange based on the HILDA model (Siegenthaler and Joos 1992) to account for non-linearities in the carbon chemistry in the ocean. The CH_4 loss terms, and parameterisation of changes in OH as function of CH_4, CO, VOC and NO_x are taken from IPCC Third Assessment Report (TAR) (IPCC 2001b). For the remaining non-CO_2 gases simple decay functions based on atmospheric lifetimes are used. Development in tropospheric O_3 as function of NO_x, CO, VOC and CH_4 are also taken from the IPCC-TAR. Forcing from sulphate aerosols (direct and indirect), fossil fuel black carbon and organic carbon aerosols, biomass burning aerosols, stratospheric O_3 and water vapour are calculated as described in IPCC-TAR and Harvey et al. (1997). Historical emissions are taken from the EDGAR-HYDE database (Van Aardenne et al. 2001).

It should be noted that when developing scenarios for the full range of climate sensitivities, we find that no climate action is required for very low climate sensitivities. Thus, we put a lower limit on climate stringency in our model at a permit price of \$1/tCeq under optimality. In these very low sensitivity cases (between 1 and 2°C sensitivity), we do not enforce the 2025/2035 peak as higher and later peaks are found to be acceptable.

In addition, at the upper end of climate sensitivities, we are bound by the capabilities of the DEEP model. At high climate sensitivities, emissions constraints simply become too large to solve. While this is not a real-world constraint, it only occurs beyond permit prices of \$5,000/tCeq, and therefore still provides a reasonable range of abatement possibilities.

Radiative forcing assumptions:	
Biomass burning	$-0.2\ Wm^{-2}$
Direct sulphate forcing	$-0.25\ Wm^{-2}$
Indirect sulphate forcing	$-0.65\ Wm^{-2}$
Black carbon forcing	$0.22\ Wm^{-2}$
Organic carbon forcing	$-0.1\ Wm^{-2}$
Tropospheric O_3 forcing due to other gases	$0.34\ Wm^{-2}$

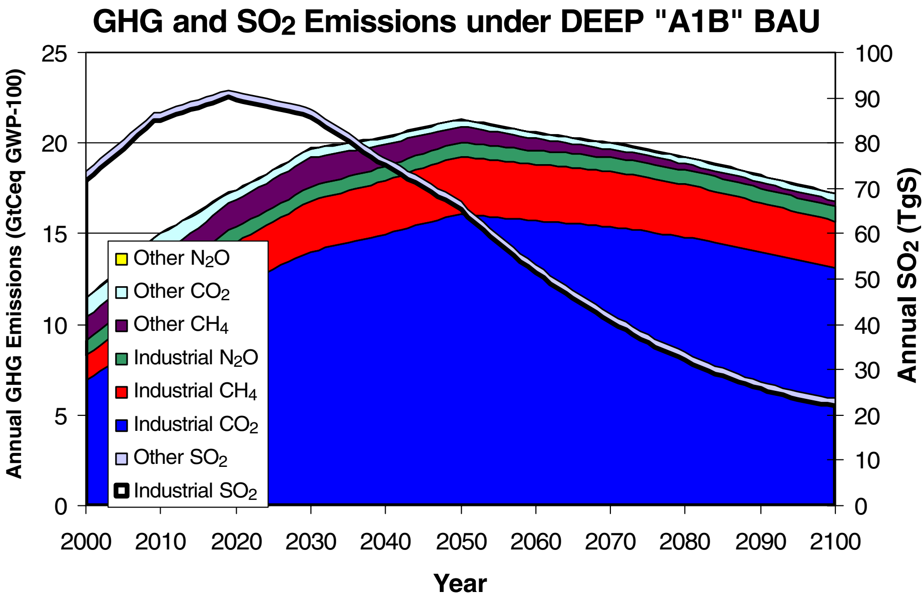

Fig. 10 Annual emissions of key gases under BAU scenario (industrial and non-industrial sources). Note: all curves are displayed in stacked format

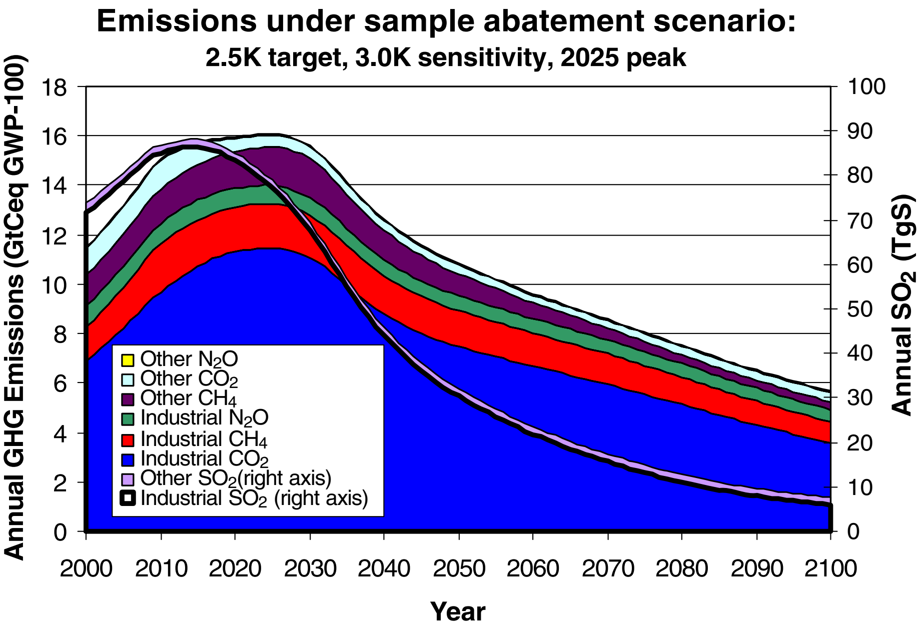

Fig. 11 Annual emissions of key gases under a sample abatement scenario. Note: all curves are displayed in stacked format

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