Ilkka Keppo, Brian C. O'Neill, and Keywan Riahi. 2007. Probabilistic temperature change projections and energy system implications of greenhouse gas emission scenarios. Technological Forecasting and Social Change, volume 74, number 7, pages 936-961.

Available online at www.sciencedirect.com
ScienceDirect
Technological Forecasting & Social Change 74 (2007) 936–961
Technological Forecasting and Social Change

Probabilistic temperature change projections and energy system implications of greenhouse gas emission scenarios

Ilkka Keppo [a,*], Brian C. O'Neill [a,b], Keywan Riahi [a]

[a] *International Institute for Applied Systems Analysis, Laxenburg, Austria*
[b] *Watson Institute for International Studies, Brown University, Providence, RI, USA*

Received 7 February 2006; received in revised form 14 May 2006; accepted 24 May 2006

Abstract

This paper explores the implications for global average temperature change of a set of reference and mitigation scenarios in a probabilistic framework. First, we use published probability density functions for climate sensitivity to investigate the likelihood of achieving targets expressed as levels or rates of global average temperature change. We find, for example, that limiting warming to 3 C above pre-industrial levels with at least a medium likelihood requires cumulative emissions reductions on the order of 30-60% below one unmitigated reference scenario by 2100, while a more favorable baseline scenario requires no reductions at all to achieve this outcome with the same likelihood. We further conclude that the rate of temperature change may prove to be more difficult to control, especially if most of the mitigation effort is postponed until later in the century. Rate of change targets of 0.1–0.2 °C/decade are unlikely to be achieved by a target for the long-term level of climate change alone. Second, we quantify relationships between mitigation costs and the likelihood of achieving various targets and show how this depends strongly on the reference scenario. Third, we explore relationships between medium-term achievements and long-term climate change outcomes. Our results suggest that atmospheric concentrations and the share of zero-carbon energy in the middle of the 21st century are key indicators of the likelihood of meeting long-term climate change goals cost-effectively. They also suggest that interim targets could be an effective means of keeping long-term target options open. Our analysis shows that least-cost mitigation strategies for reaching low climate change targets include a wide portfolio of reduction measures. In particular, fundamental long-term structural changes in the energy system in these scenarios are a

---

* Corresponding author.
E-mail address: keppo@iiasa.ac.a (I. Keppo).

doi:10.1016/j.techfore.2006.05.024

necessary but not sufficient condition to achieve high likelihoods for low temperature targets. The cost-effective portfolio of emissions reductions must also address demand-side measures and include mitigation options in the industry, agriculture, and the forest sector.

Keywords: Climate change; Energy modeling; Climate sensitivity; Uncertainty analysis

1. Introduction

The IIASA mitigation scenarios [1] were designed to meet various targets set in terms of radiative forcing in 2100. Radiative forcing lies near the center of a causal chain that runs from human activities to changes in emissions, concentrations, forcing, and climate, and ultimately to impacts. There is uncertainty in each link of this chain. Scenarios that meet the same radiative forcing goal but assume different development pathways, such as the mitigation scenarios in [1], explore uncertainties near the start of this chain. Here we explore uncertainties toward the end of the chain, specifically the range of possible global average temperature change outcomes implied by individual radiative forcing pathways.

Evaluating the global average temperature changes that result from mitigation scenarios is important for assessing the potential benefits of climate change mitigation policies, in terms of avoided damages. While it is the spatial pattern of various aspects of climate change (temperature, precipitation, extreme events, seasonality, etc.) that determine the impacts, the rates and levels of global average temperature change can serve as a reasonable first-order proxy. These global metrics are also useful in discussions of global climate policy, in particular regarding strategies to avoid dangerous interference with the climate system, as called for by the United Nations Framework Convention on Climate Change (UNFCCC). A growing body of literature has begun to associate particular levels and rates of change with impacts that may be considered dangerous ([2–8]), and policy proposals, such as the European Union (EU) target to limit warming to 2 °C above the pre-industrial level, have been advanced on these grounds.

To account for uncertainty in climate change projections is important, since currently it is not possible to predict with precision what rate and level of warming will result from a given radiative forcing path. The most important climate system characteristic that links radiative forcing pathways to climate outcomes is climate sensitivity. This is conventionally defined as the equilibrium global mean temperature change that results from a doubling of the pre-industrial CO_2 concentration. Not only is the value of this parameter unknown, but there is disagreement on the quantification of its uncertainty as well. A number of different probability density functions (PDFs) for climate sensitivity have been estimated [9–13]. Thus, achieving a given concentration target will only achieve a given temperature outcome with a certain degree of likelihood, and that likelihood itself is uncertain. While this state of affairs means we cannot say precisely how much climate change will be reduced by a given mitigation scenario, we *can* begin to estimate how much a given mitigation scenario will increase our confidence in meeting a certain temperature change target.

Our aim is to explore the probabilistic implications of a *limited* set of illustrative emissions scenarios that cover the range of baseline and stabilization uncertainties in the literature. In this study we model the probabilistic temperature change consequences of 11 scenarios: the revised A2r and B1 reference scenarios [1], along with nine mitigation scenarios that are based on one of these reference development pathways but limit radiative forcing to a range of targets in 2100. The two baseline scenarios bracket the upper and lower quadrants of baseline emissions in the literature [14] and hence the magnitudes of climate change. In addition, they show pronounced differences with respect to income and demographic trends, and thus describe contrasting worlds with respect to possible vulnerability to climate change. We use these two scenarios as the basis of a systematic sensitivity analysis for a wide range of climate targets, from very high radiative forcing targets (8.4 W/m^2) to very low targets (2.8 W/m^2). Clearly, our set of scenarios does not cover all possible future climate outcomes, but shows the dynamics of emissions pathways and their probabilistic interpretation given a large variation in the underlying socio-economic, demographic, and technological assumptions. An overview of the scenarios, which includes a qualitative and quantitative description of the underlying assumptions and results with respect to the effect of climate mitigation, can be found in this Special Issue [1]. Here we use the scenario results [1] to address four main questions:

1) How likely are the scenarios to stay below a range of temperature increase targets?
2) How likely are they to stay below a range of rate-of-change targets?
3) What are the costs of increasing the probability of meeting any particular climate change target, and what combination of technological measures is needed and have the largest potential?
4) What are the medium-term conditions (in terms of atmospheric concentrations and energy system characteristics) associated with various long-term climate change outcomes?

The following sections first present the basic methodology. Subsequently, we address each of these questions in turn.

2. Methodology

The IIASA Integrated Assessment (IA) Modeling Framework was used to develop the scenarios presented in this paper. The framework links a set of detailed disciplinary models that operate at alternative spatial resolution. The framework covers all greenhouse gas (GHG)-emitting sectors, including agriculture, forestry, energy, and industrial sources for a full basket of greenhouse gases and the main air pollutants — CO_2, CH_4, N_2O, NO_x, volatile organic compounds (VOCs), CO, SO_2, CF_4, C_2F_6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca and SF_6.

Model integration is achieved through hard and soft linkages between the individual components to ensure internal scenario consistency and plausibility [1]. Regional, national, and spatially explicit demographic and economic projections serve as exogenous inputs to the three principal models of the IA framework: The Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) [15], the Agro-economical Zones-Basic Linked System(AEZ-BLS) agricultural framework [16], and the multigas Model for Energy Supply Strategy Alternatives and their General Environmental Impact-macro-economic (MESSAGE-MACRO) model [17,18].

MESSAGE-MACRO stands at the heart of the full assessment framework, as it integrates agricultural and forest sector information from the detailed DIMA and AEZ-BLS models. The MESSAGE-MACRO framework comprises the systems engineering optimization model MESSAGE

[19] and the top-down macroeconomic equilibrium model MACRO [20].[1] Linking the two models iteratively permits the estimation of internally consistent scenarios of energy prices and energy systems costs-derived from a detailed systems engineering model (MESSAGE) with economic growth and energy demand projections obtained from a macroeconomic model (MACRO). The framework maps the entire energy system with all its interdependencies, from resource extraction, imports and exports, conversion, transport and distribution to end-use services. Its principal results comprise estimates of technology-specific multi-sector response strategies for a range of alternative climate stabilization targets.[2]

A typical scenario development cycle [1] comprises four main steps:

1) Development of spatially explicit economic and demographic projections;
2) Estimation of spatially explicit national and regional (dynamic) supply curves for forest sinks and bioenergy supply, and agriculture-related drivers of GHG emissions;
3) Incorporation of this information into the MESSAGE-MACRO model at the level of 11 world-regions;
4) Development of multi-gas mitigation scenarios with MESSAGE-MACRO.

The latter model identifies the least-cost portfolio of mitigation technologies, given a specific long-term climate target. The choice of the individual mitigation options across gases and sectors is driven by the relative economics of the abatement measures, assuming full temporal and spatial flexibility (i.e., emissions-reduction measures are assumed to occur when and where they are cheapest to implement). For the intertemporal optimization, we use a discount rate of 5% throughout all of the calculations reported here.

Technological change assumptions in the scenarios operate both at the level of aggregate trends, such as macro-economic productivity growth or resource efficiency, as well as at the sectoral level (e.g., crop yields in agriculture). The detailed 'bottom-up' energy sector model MESSAGE deploys technology-specific assumptions on availability, performance, and costs of energy conversion technologies, the dynamics of which unfold over time. Improvements in technology costs are assumed to be particularly rapid in the technology-dynamic B1 scenarios, in contrast to the conservative technology outlook of A2r [1].[3] The mitigation scenarios maintain the assumptions about technology costs used in the baseline

---

[1] The systems engineering model MESSAGE projects the optimal allocation of investments across sectors by minimizing total system costs to satisfy a given demand. MACRO is a top-down macroeconomic equilibrium model in which capital stock, available labor, and energy inputs determine the total output of an economy according to a nested constant elasticity of substitution (CES) production function.

[2] In our approach we employ a bottom-up methodology, in which emissions reductions are modeled predominantly on a technology-specific basis for all relevant sectors (energy, agriculture, and forestry). For emissions sources with comparatively large uncertainties (methane from rice cultivation and enteric fermentation; and N_2O from soil) we use marginal abatement cost curves [21]. The large uncertainties that exist in the feasibility and costs of these mitigation options mean that we do not assume any major changes in the mitigation potential of these sources in the long run [17].

[3] The specific shape of the emissions pathways derived by our methodology and assumptions has important implications for the resulting climate outcomes. Using, for example, an alternative discount rate or different parameterization of technological change affects the timing of mitigation and thus also the computed probabilities of temperature change (and in particular the rate of change). Lower discount rates and higher learning rates as compared to our assumptions could, for example, lead to earlier emissions reductions. The emphasis of our paper is on the probabilistic interpretation of a limited set of scenarios for which detailed and internally plausible and consistent quantifications exist. A promising area of future research would thus be to carry out a sensitivity analysis with respect to other uncertain parameters.

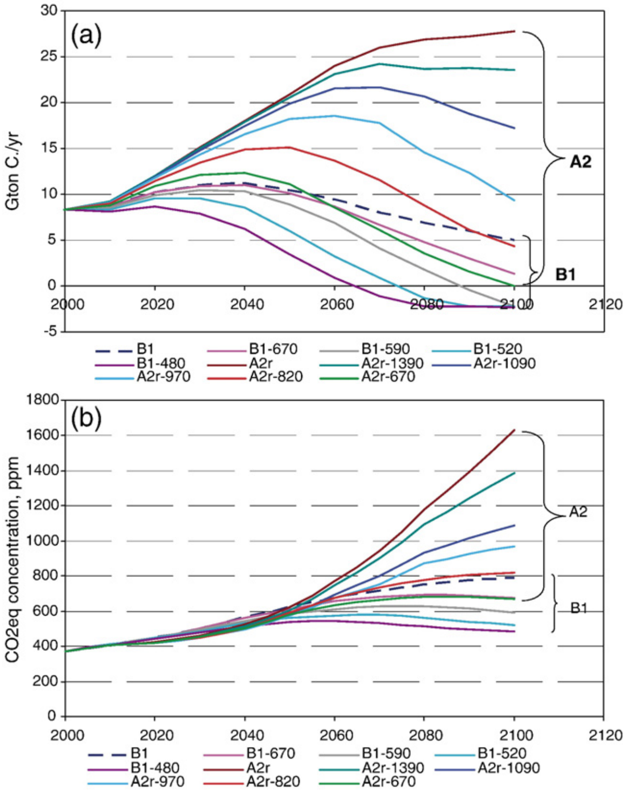

Fig. 1. (a) CO_2 emissions and (b) CO_2-equivalent concentrations of the mitigated and unmitigated emission scenarios. (For a color version of the paper, see the electronic edition).

scenarios, but impose a constraint on radiative forcing — expressed in terms of equivalent CO_2 concentration — in the year 2100.[4,5]

We use the simple climate model MAGICC (Model to Assess Greenhouse-gas Induced Climate Change) [22] to derive the stabilization scenarios. MESSAGE and MAGICC are run in an iterative mode: cumulative carbon equivalent emissions are used as a constraint in MESSAGE, and the radiative forcing consequences of the resulting emissions pathways are computed with MAGICC. The cumulative emissions target is adjusted until the desired value of radiative forcing in the target year is achieved. The true CO_2 emission paths, derived from the MESSAGE-MACRO runs [1], and the CO_2 equivalent concentrations of the scenarios studied are shown in Fig. 1, and the main climate and emissions indicators of these runs are collected in Table 1. The mitigation scenarios are named according to their CO_2

---

[4] We define CO_2-equivalent concentrations as the CO_2 concentration that would, by itself, produce the same radiative forcing as the combination of all radiatively active gases in the scenarios. We have defined the year 2000 as our base year and set CO_2 concentrations in 2000 as equal to CO_2-equivalent concentration. If pre-industrial times were used as the base year, CO_2-equivalent concentrations would be approximately 3% lower.

[5] The direct aerosol forcing is assumed to be -0.4 W/m^2 in 1990 and for indirect aerosol forcing in 1990 we use the value of -0.8 W/m^2.

Table 1
Basic climate and emission data for the year 2100 for all emissions scenarios

	Radiative forcing (W/m^2)	CO_2 equivalent concentration (ppm)	True CO_2 concentration (ppm)	Maximum temperature increase with a climate sensitivity of 2.5 °C	Reduction in cumulative CO_2-eq emissions in 2100	Annual CO_2eq emissions below the baseline in year 2100	CO_2 emissions in 2100 (GtC)
A2r	9.3	1630	917	4.3	0%	0%	28
A2r-1390	8.4	1388	866	3.9	9%	21%	24
A2r-1090	7.1	1088	797	3.4	19%	43%	17
A2r-970	6.5	971	696	3.2	31%	64%	9
Ar-820	5.6	819	588	2.8	44%	78%	4
A2r-670	4.5	668	490	2.3	57%	91%	0
B1	5.4	792	532	2.7	0%	0%	5
B1-670	4.6	673	496	2.4	12%	55%	1
B1-590	3.9	591	445	2.1	27%	96%	−2
B1-520	3.2	522	397	1.8	43%	96%	−2
B1-480	2.8	482	368	1.6	54%	96%	−2

Temperature changes increases to pre-industrial values. Global warming potentials (GWPs) are used to calculate CO_2-equivalent emissions reductions for illustrative purposes.

equivalent concentration targets in 2100. Of these scenarios, the three lowest B1 mitigation scenarios are overshoot scenarios with respect to temperature (peaks occur between 2070 and 2090; all B1 mitigation scenarios, as well as the lowest A2r mitigation scenario, overshoot with respect to equivalent CO_2 concentration). For other scenarios the maximum temperature always refers to the year 2100.

To quantify uncertainty in global average temperature change from these scenarios, we treat climate sensitivity as uncertain using two different PDFs (Fig. 2). The first one assumes that the long-stated IPCC uncertainty range of 1.5 °C to 4.5 °C is the 90% confidence range and that the distribution is log-normal (by Wigley and Raper [9], abbreviated as WR). The second one was constructed by Andronova and Schlesinger [10], (abbreviated as AS and based on distribution T2, which includes solar and aerosol forcing) by employing a simple climate model in a Monte Carlo analysis of historical forcing and global average temperature change.

Although other choices are possible, these two PDFs capture principal differences among available estimates. As Fig. 2 shows, the WR and AS distributions differ not only in their median values, but also in the likelihood assigned to more extreme outcomes. In particular, the AS PDF reflects a substantially greater chance of high climate sensitivity. According to AS, there is a 10% chance that sensitivity is greater than about 5 °C, while according to WR there is a 10% chance that it is greater than about 4 °C. These differences in the tails of the distributions can have large implications for the chances of exceeding particular climate targets, one of the primary goals of our analysis.

We calculate global average temperature increases for the mitigation scenarios, again using the simple climate model MAGICC for a range of climate sensitivities. Specifically, for each emissions scenario we calculate the resulting temperature change using climate sensitivities from 0.1 to 10 (with a step size of 0.1) and express the results in the form of two time-dependent probability distributions using the two PDFs described above. In MAGICC, we include a feedback between climate and the carbon cycle, use best estimate values for parameters that describe aerosol forcing, carbon cycle terrestrial sinks, and ocean diffusivity, and assume a variable ocean thermohaline circulation. With this approach, uncertainty in

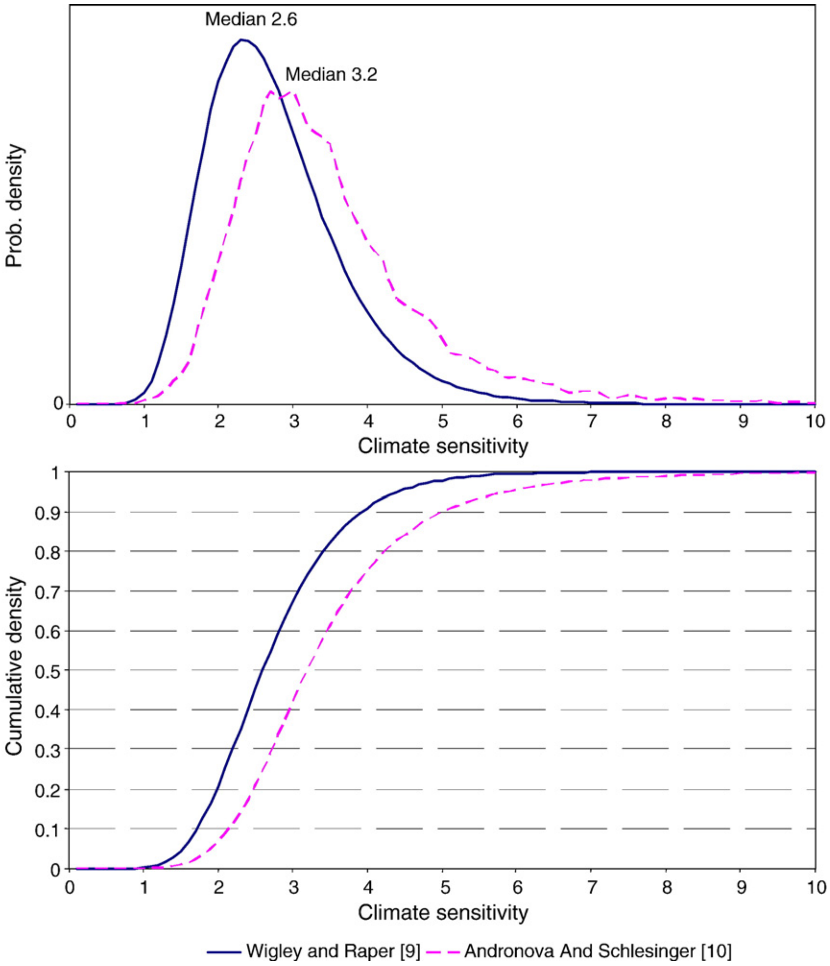

Fig. 2. The probability density functions used for climate sensitivity in this study.

climate change outcomes reflects only the uncertainty in climate sensitivity, and not in GHG cycles, ocean mixing, or radiative forcing relationships. While this simplification does not affect long-term temperature change outcomes, it implies an incomplete accounting for uncertainty in transient temperature changes. In particular, uncertainties in ocean mixing, radiative forcing factors, and climate sensitivity are correlated so that, for example, a high climate sensitivity implies more strongly negative sulfate radiative forcing factor values and vice-versa [10,23]. Thus, the results presented here should be seen as a first-order estimate of the uncertainty in rates and levels of temperature change. Nonetheless, since climate sensitivity is the principal uncertainty, and we consider two substantially different estimates of the uncertainty distribution for this parameter, our results likely capture a substantial portion of the range of plausible future outcomes. As some evidence of this, our simplified approach can still reasonably simulate the historical record. The IPCC identifies 0.6±0.2 °C as the 95% confidence interval for observed global average temperature change over the period 1861–2000. This range of temperature change corresponds either to the 87% (WR) or 95% (AS) confidence interval of projected warming using the two PDFs for climate sensitivity we adopt, combined with best estimates of radiative forcing factors and ocean diffusivity.

Several studies have explored the consequences of climate sensitivity uncertainty for climate change outcomes using probabilistic approaches similar to the method described here [24–30]. Our results complement these studies by adding to the growing body of literature that associates mitigation paths with estimates of (uncertain) levels and rates of climate change. In addition, because our study is based on a set of mitigation scenarios developed using a detailed, multi-gas integrated assessment framework, we can go beyond previous work by analyzing the cost associated with reducing the risk of crossing various climate change thresholds. Furthermore, we go beyond costs to identify the specific energy system changes that achieve such risk reductions, and examine their dependence on assumptions that concern the socio-economic development paths.

3. Probability of exceeding a temperature target

Fig. 3 shows the probability distribution functions for temperature change by 2100 for the baseline scenarios B1 and A2r and the mitigation scenarios B1-480 and A2r-670, using both the WR [9] and the AS [10] PDFs for climate sensitivity.

Emissions mitigation not only moves the distributions to the left (toward less warming), but also reduces the range of the 90% confidence interval. Using the WR distribution for the A2r scenario,

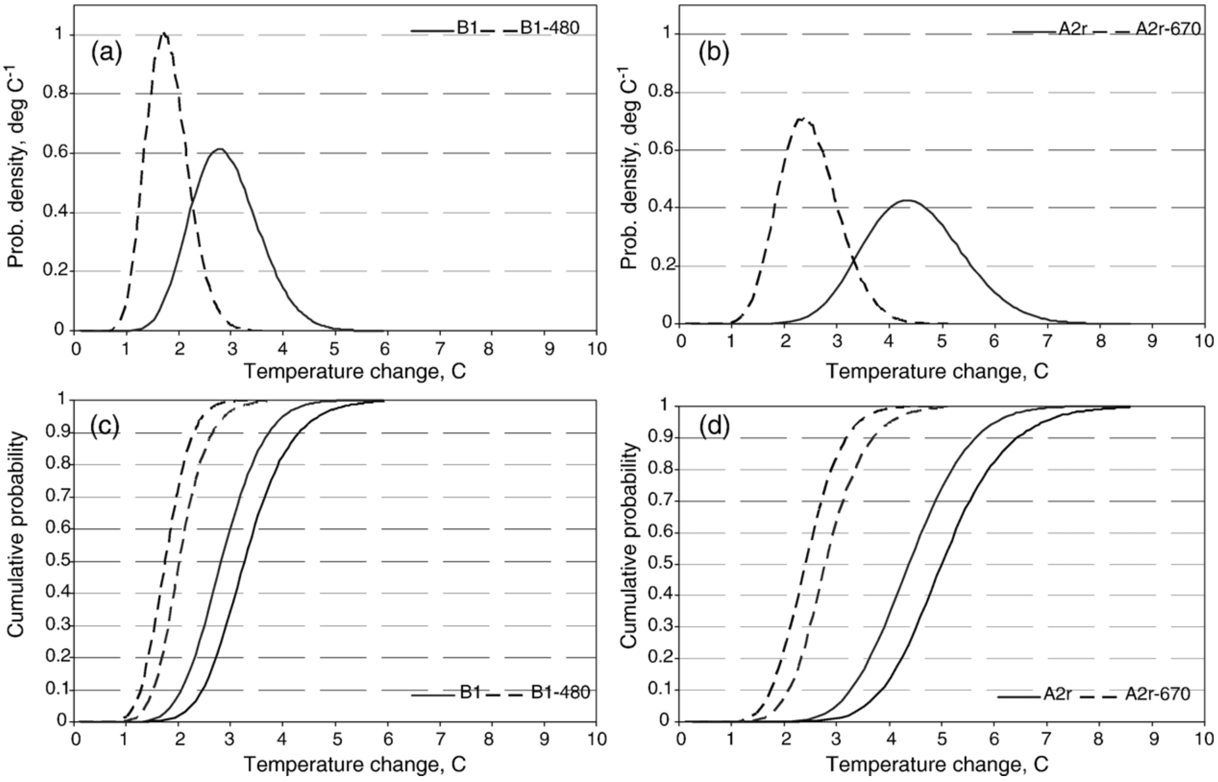

Fig. 3. Distributions for temperature change since pre-industrial times for (a, c) B1, B1-480, and (b, d) A2r and A2r-670. The curves to the right in each pair shown in the lower panels use the PDF of AS [10], while all others use the WR [9] distribution (unless otherwise noted, temperature changes are expressed relative to pre-industrial values throughout the paper).

mitigation shifts the median temperature change from 4.4 to 2.4 °C and reduces the 90% confidence interval from 3.1–6.0 °C (a 2.9 °C spread) to 1.6–3.4 °C (only a 1.8 °C spread). Changes are similar for the B1 scenario, with the median temperature change dropping from 2.8 to 1.6 °C with mitigation. The cumulative distributions shown in the lower panels of Fig. 3 indicate differences in outcomes when using the AS PDF rather than the WR PDF, and can be used to derive probabilities for remaining below a specific target before 2100. Table 2 provides a more complete listing of such results across all scenarios. A light gray background in Table 2 indicates that the probability of remaining below a given temperature target is 33–66%, which in IPCC terminology corresponds to 'medium likelihood' [31]. Darker gray refers to probabilities above 66%, considered at least 'likely' in IPCC terminology.

As Table 2 shows, only the mitigation scenario with CO_2-equivalent concentrations below 500 ppmv (parts per million by volume) has at least a 'medium likelihood' to stay below a temperature target of 2 °C with both climate sensitivity PDFs. Lower temperature targets are practically unreachable in most scenarios. Staying below the target of 3 °C has at least a 'medium likelihood' for all B1 scenarios, including the baseline. In contrast, A2r scenarios must mitigate to 670–970 ppm CO_2-eq (depending on the climate sensitivity PDF) to stay below 3 °C with the same likelihood, which, according to Table 1, requires reductions in cumulative emissions of 31–57%. Targets of 3.5 °C and above are required for at least half of the A2r scenarios to have a 'medium likelihood' of achieving them.

Comparing our results with previous studies indicates that our probability range is fairly similar. Hare and Meinshausen [24] report a probability range of 5–40% for their 500 ppm CO_2-eq scenario and a

Table 2
Probabilities for staying below set temperature targets for a group of mitigation scenarios and for PDFs WR [9] and AS [10]

Scenario	Clim.sens. PDF	Temp. incr. (°C)						
		1	1.5	2	2.5	3	3.5	4
A2r	AS	0%	0%	0%	0%	1%	3%	11%
	WR	0%	0%	0%	1%	4%	13%	30%
A2r-1390	AS	0%	0%	0%	0%	2%	9%	21%
	WR	0%	0%	0%	2%	9%	25%	***45%***
A2r-1090	AS	0%	0%	0%	1%	9%	25%	***50%***
	WR	0%	0%	1%	7%	25%	***50%***	***74%***
A2r-970	AS	0%	0%	0%	3%	14%	***38%***	***61%***
	WR	0%	0%	2%	13%	***35%***	***63%***	***82%***
Ar-820	AS	0%	0%	1%	9%	29%	***57%***	***81%***
	WR	0%	0%	7%	25%	***55%***	***80%***	***94%***
A2r-670	AS	0%	1%	6%	29%	***61%***	***84%***	***95%***
	WR	0%	3%	21%	***55%***	***82%***	***96%***	***99%***
B1	AS	0%	0%	1%	11%	***33%***	***61%***	***83%***
	WR	0%	0%	7%	30%	***59%***	***82%***	***95%***
B1-670	AS	0%	0%	5%	25%	***57%***	***81%***	***93%***
	WR	0%	2%	16%	***50%***	***80%***	***94%***	***99%***
B1-590	AS	0%	1%	14%	***46%***	***77%***	***92%***	***98%***
	WR	0%	4%	***35%***	***71%***	***92%***	***99%***	***100%***
B1-520	AS	0%	3%	29%	***68%***	***91%***	***98%***	***100%***
	WR	0%	13%	***55%***	***86%***	***98%***	***100%***	***100%***
B1-480	AS	0%	9%	***46%***	***84%***	***96%***	***99%***	***100%***
	WR	1%	25%	***71%***	***96%***	***100%***	***100%***	***100%***

Dark-shaded boxes indicate a likelihood of >66% of achieving a target and the light shaded boxes refer to probabilities of 33% to 66%.

range of 31–68% for the 440 ppm CO_2-eq case for reaching a 2 °C target. Schneider and Mastrandrea [29] have a probability of 22% for staying below the same target with CO_2-eq levels to stabilize at 600 ppm and a probability of 55% for a scenario with a CO_2-eq of 500 ppm.[6]

Meinshausen [23] reports probabilities for transient temperature increases in 2100. He shows for a 2 °C target probabilities of approximately 55–62% for a 475 ppm CO_2-eq stabilization case and around 30% for a 550 ppm CO_2-eq case using the WR PDF. If the AR PDF is used instead, the probabilities are 22–30% (475 ppm) and 10% (550 ppm). We obtain approximately similar probabilities with a concentration target of 590 ppm. The differences likely result from the different assumptions made concerning the climate model parameters. We assumed best-guess parameter values for ocean diffusivity and aerosol forcing factors, whereas Meinshausen [23] accounts for correlations between these and the climate sensitivity uncertainty (see Section 2).

Our results also highlight the importance of the baseline development path. For example, of the A2r scenarios only the most stringent mitigation scenario, which reduces forcing in 2100 from 9.3 to 4.5 W/m^2, would be any more likely to reach a given temperature target than the unmitigated baseline scenario B1. This shows how developments not necessarily directly related to the climate change regime play a crucial role in defining how difficult it is to reach particular targets.

Furthermore, results also show that the uncertainty concerning the choice of PDF for climate sensitivity creates a rather sizable range of probabilities for achieving climate targets. For example, the most stringent mitigation scenario imposed on the A2r baseline, A2r-670, has a probability of reaching a target of 2 °C that is more than three times as high according to the PDF of WR as it is according to the PDF of AS. This ratio is still almost two for a target of 2.5 °C. This implies that the uncertainty included in the choice of the PDFs themselves is also significant.

4. Probability of exceeding a rate-of-change target

Impacts are sensitive not only to the amount of climate change, but also to its rate, since faster rates of change make it more difficult or even impossible for ecosystems or society to adapt. We therefore calculate the likelihood of each mitigation scenario staying below a target expressed in terms of rate of temperature change. While no definitive threshold can be defined for rates of change beyond which adaptation is precluded, previous studies indicate that ecosystems may have difficulty adapting to sustained warming beyond 0.1–0.2 °C/decade [32,33,4]. The rate of change has already crossed the lower of these thresholds; based on the data given in Jones et al. [34], rate of change reached 0.16 °C/decade in 2004, calculated with both a 10-year average and 30-year average.

We emphasize that the mitigation scenarios considered here were not constrained to meet a temperature target; they were constrained only to meet a radiative forcing target in 2100. While this long-term target does place an indirect constraint on the temperature change experienced on average over the century, there is no explicit limit on rates of change over shorter periods. Rather, emissions (and therefore climate change) paths are determined only by the least-cost solution to achieve the radiative forcing target in 2100. These solutions tend to favor delaying reductions to later in the century, which leads to higher rates of change over the next few decades than would be the case if reductions were not

---

[6] The stabilization levels used in [24] and [25] are generally reached only after 2100.

delayed.[7] Therefore, the rates of warming experienced in these scenarios do not reflect what might be achievable, but rather reflect only what might be experienced in the absence of any specific constraint on rates.

The PDFs that describe rate-of-change outcomes are formulated based on the maximum rate of change experienced during the century for the full range of climate sensitivities studied. However, there are many ways to calculate the maximum rate of change. If short-lived peaks in the rate of change are important to impacts, rates should be calculated over short periods (e.g., 5 years). Conversely, if it is sustained high rates of change over several decades that are dangerous, a 30-year average or 30 years of consecutive 5-year periods of high rates of change could be used as the metric.

Fig. 4[8] shows how large an impact the definition of the rate of change can have. For example, if a maximum rate of change below 0.2 °C is set as a target and the maximum rate of change is defined as the highest 5-year average encountered, scenario B1-480 has a probability of only 3% of reaching this target. However, if the maximum rate of change is calculated based on the highest rate exceeded for six consecutive 5-year periods, the probability jumps to 30%. Using the highest 30-year average rate of change results in a probability between these two, approximately 20%. For the remainder of this paper, our definition for the rate of change is the highest 30-year average rate of change encountered during the century, but the sensitivity to this choice is important to keep in mind.

Fig. 5 shows the cumulative probabilities for the baseline scenarios B1 and A2r and the most stringent mitigation targets studied here, B1-480 and A2r-670. Table 3 collects results for all scenarios; as with Table 2, the combinations of scenarios and targets with a probability over 66% are shaded dark gray, and those below 66% but above 33% have light gray shading.

Fig. 5 and Table 3 show that experiencing a maximum increase of 0.2 °C/decade or less is rather unlikely if no specific targets concerning the rate of change are imposed. The baseline A2r is virtually certain not to reach this target and even the mitigation scenario A2r-670 has a probability of only about 1–3% of limiting the maximum rate of change to less than 0.2 °C/decade. The mitigation scenario B1-480 has the highest probability of staying below this target, but even in this case the likelihood ranges only from 6 to 21%, depending on the PDF used. Thus, for a 0.2 °C/decade target, a long-term target alone is insufficient to limit the maximum rates of warming.

If a warming rate of 0.3 °C/decade is deemed acceptable, a long-term target alone produces a high chance of staying below the rate limit only in the B1 scenario with relatively stringent mitigation. In this, mitigation to 2.8 W/m^2 (480 CO$_2$-eq) increases the chance of meeting the rate target from 25–50% to a likely 70–90%. In contrast, in the A2r scenario, mitigation to a 4.5 W/m^2 target (670 CO$_2$-eq) in 2100 increases the chance of meeting the rate target from essentially zero (in the unmitigated baseline) to only 20–40%. Thus it appears that only relatively low long-term targets, perhaps requiring favorable baseline development paths, can also meet rate targets without additional constraints designed to produce slower warming.

The timing of the highest rates of change depends mainly on the magnitude of the mitigation efforts and the underlying baseline scenario. For the A2 scenarios with fairly modest climate targets, the highest

---

[7] However, a sharp simultaneous reduction of GHG emissions and aerosols can lead to high rates of change, especially if the rate of change is calculated based on a rather short time step. We use 30-year average to estimate the rate of change and therefore the peaks caused by a rapid reduction of sulfur emissions are mostly averaged out. If a 5-year time step is used, peaks caused by a reduction of sulfur emissions become much more important in defining the highest rates of change experienced.

[8] The discontinuities shown in Figs. 4 and 5 are caused by the discrete step size used for climate sensitivity in the climate model runs.

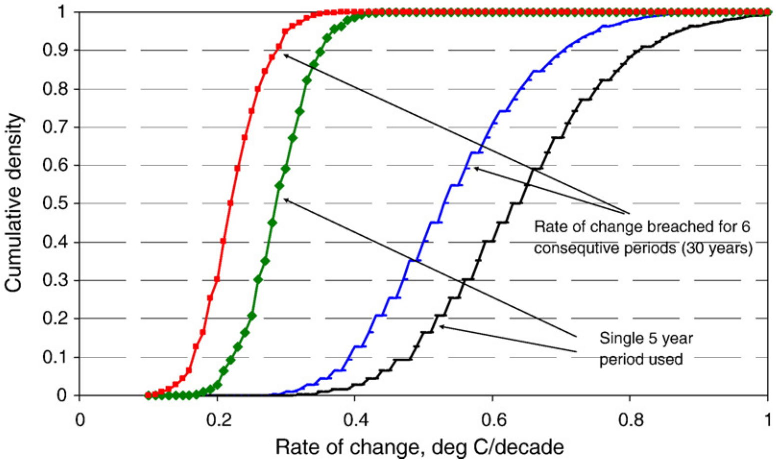

Fig. 4. The difference between the choice of sustained and short-lived peaks in rates of change. A2r on the right and B1-480 on the left. WR [9] climate sensitivity distribution used.

warming rates are experienced toward the end of the century, while for the A2 scenarios with stronger mitigation the highest rates are observed around 2060. Low-mitigation B1 scenarios experience the highest rates around the year 2050, and the shorter term (i.e., around 2030) becomes relatively more important with increased mitigation, with the rates of change experienced remaining lower than the 2030 values throughout the rest of the century. However, the rates experienced in the short term are, in absolute terms, still lower with stronger mitigation.

Comparing Table 3 with Table 2 shows that, although mitigation designed to meet a long-term radiative forcing target clearly also improves the probability for reaching a rate-of-change target, the maximum rates of change of 0.1–0.2 °C/decade are more difficult to reach than the temperature targets of 1.5–2.5 °C, which could be considered comparable.[9] This is especially the case with the A2r scenario and its mitigation variants.

Another central finding is that the baseline development path has important implications for the probability of rate-of-change targets, even at similar levels of stabilization. As illustrated in Table 3, it is more likely to achieve any given rate of change target in the B1-670 than in the A2r-670 scenario. This occurs even though the two scenarios have, by definition, very similar likelihoods of achieving absolute temperature-change targets (Table 2; scenario A2r-670 is even slightly more likely to achieve these targets). The principal reason for this result is that the emissions pathways to achieve the long-term forcing target differ considerably between the scenarios. The carbon intensity of the baseline scenarios,

---

[9] ‘Comparable’ value for the 30-year average rate is estimated by assuming that the rate of change starts from zero in 2000, increases linearly to its ‘comparable’ value by 2035, stays there for 30 years and returns back to zero by 2100. For rates of 0.1–0.2 °C/decade this path corresponds to a temperature increase of 0.65–1.3 °C over the century, or some 1.25 to 1.9 °C compared to pre-industrial times (if an increase of 0.6 °C is assumed by the year 2000). Since, in reality, the rate of change was not zero in 2000 and in many of the scenarios a non-zero rate is observed also in 2100, the upper limit of this ‘comparable range’ is increased to 2.5 °C. This would, in a similar, symmetric rate-of-change development, correspond to initial and final rates of 0.17 °C/decade for the 0.2 °C/decade rate-of-change target. Combining the targets 1.5 °C and 0.1 °C/decade would correspondingly lead to initial and final rates of 0.07 °C/decade. However, all these comparisons are meant only as illustrative and should not be interpreted otherwise.

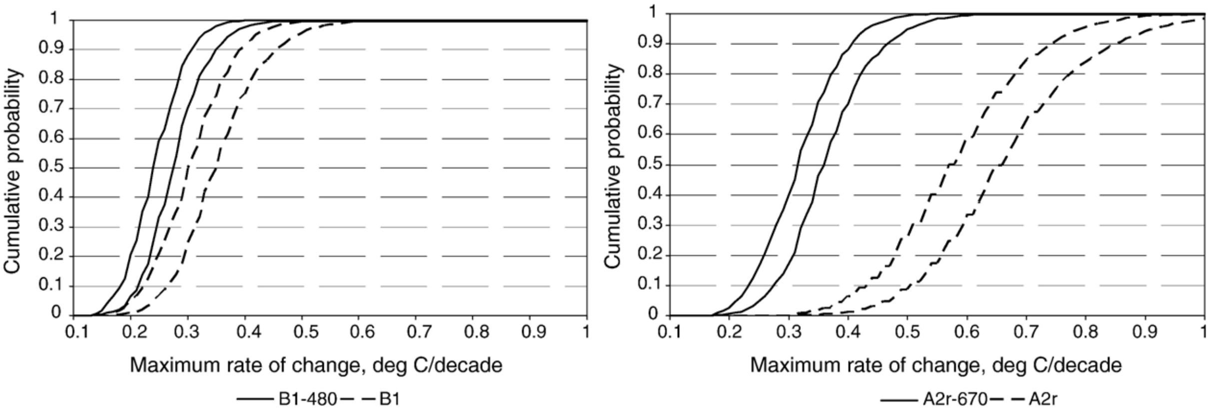

Fig. 5. Distributions for maximum rate of temperature change experienced until the year 2100. Calculated based on the maximum 30-year average experienced. The curves to the right use the PDF of AS [10], while the others are based on the WR [9] distribution.

and hence assumptions concerning technological change, energy demand, and the availability and costs of clean and advanced technologies, critically affect the timing of mitigation. Generally, inertia of the energy system is stronger in high-emissions baseline scenarios (A2r), which tend to postpone mitigation to later points in time. In contrast, B1 permits the more rapid penetration of clean and advanced technologies over

Table 3
Probabilities for reaching a 'rate of temperature change' target. PDFs used are WR [9] and AS [10]

Scenario	Clim.sens. PDF	Rate of temp. incr. (°C)							
		0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.5
A2r	AS	0%	0%	0%	0%	0%	0%	1%	9%
	WR	0%	0%	0%	0%	0%	2%	7%	25%
A2r-1390	AS	0%	0%	0%	0%	0%	1%	2%	14%
	WR	0%	0%	0%	0%	1%	3%	9%	***35%***
A2r-1090	AS	0%	0%	0%	0%	1%	3%	11%	***42%***
	WR	0%	0%	0%	1%	4%	13%	30%	***67%***
A2r-970	AS	0%	0%	0%	1%	2%	9%	25%	***65%***
	WR	0%	0%	0%	3%	9%	25%	***50%***	***84%***
Ar-820	AS	0%	0%	0%	1%	5%	17%	***38%***	***79%***
	WR	0%	0%	0%	4%	16%	***40%***	***63%***	***93%***
A2r-670	AS	0%	0%	1%	5%	17%	***46%***	***70%***	***95%***
	WR	0%	0%	3%	16%	***40%***	***71%***	***88%***	***99%***
B1	AS	0%	0%	1%	6%	25%	***50%***	***75%***	***96%***
	WR	0%	0%	4%	21%	***50%***	***74%***	***91%***	***100%***
B1-670	AS	0%	0%	1%	9%	29%	***57%***	***81%***	***97%***
	WR	0%	0%	4%	25%	***55%***	***80%***	***94%***	***100%***
B1-590	AS	0%	0%	2%	17%	***46%***	***75%***	***91%***	***99%***
	WR	0%	1%	9%	***40%***	***71%***	***91%***	***98%***	***100%***
B1-520	AS	0%	0%	5%	25%	***61%***	***85%***	***95%***	***100%***
	WR	0%	2%	16%	***50%***	***82%***	***96%***	***99%***	***100%***
B1-480	AS	0%	0%	6%	***33%***	***70%***	***90%***	***98%***	***100%***
	WR	0%	2%	21%	***59%***	***88%***	***98%***	***100%***	***100%***

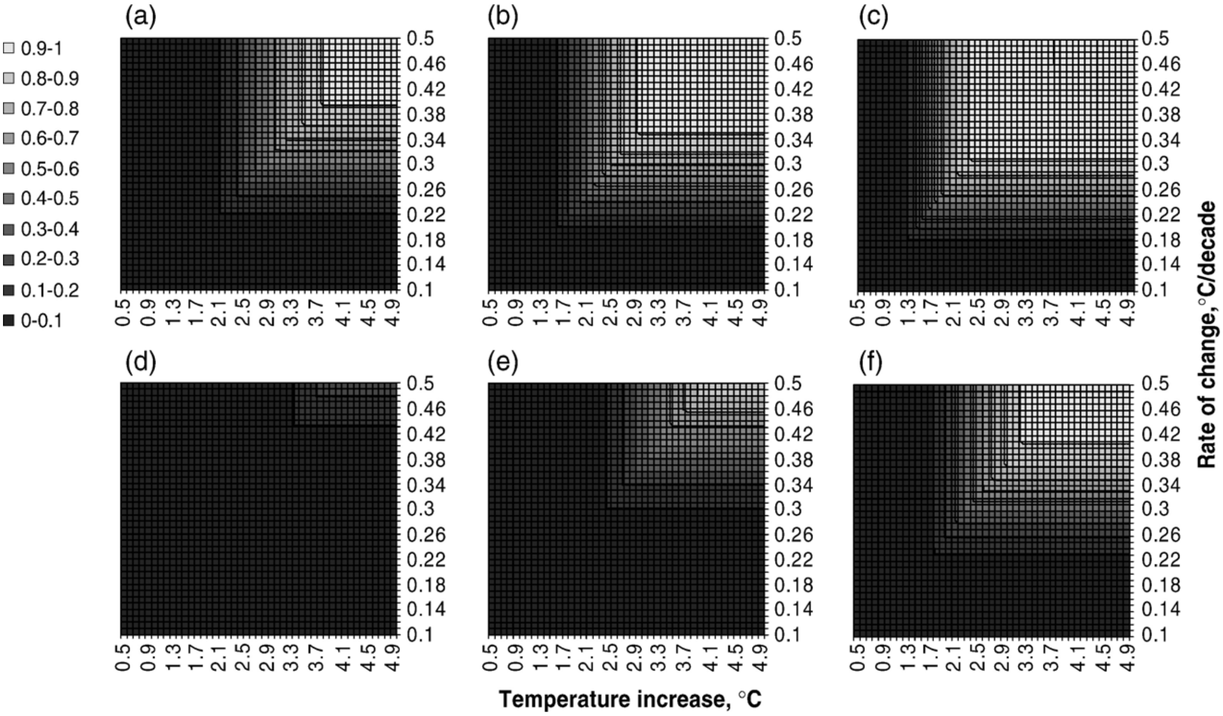

Fig. 6. Probabilities of meeting both a rate of change target and a temperature increase target for selected scenarios (upper row from left to right: B1, B1-590, B1-480; lower row A2r, A2r-970, A2r-670) using the Wigley and Raper [9] PDF.

the short term, which leads to a smoother transition and thus lower rates of temperature change. These results emphasize the finding that long-term targets alone might not necessarily be effective in limiting the rates of climate change.

To link the results for both rates and levels of climate change, we present them in a manner closely related to the 'Tolerable Windows' and 'Safe Landing' approaches' [35,36]. Fig. 6 presents the joint likelihood of scenarios reaching two targets simultaneously:

1) An absolute limit for temperature increase from pre-industrial times (see Chapter 3)
2) A limit for the rate of temperature change calculated based on a 30-year average.

The values shown in Fig. 6 are calculated by looking at the target pairs (target 1, target 2 above) and defining which one of these two targets requires a lower climate sensitivity to be fulfilled. The probability attached to this lower climate sensitivity defines the probability of reaching both of these targets. In other words, we first define which target is the constraining one for each pair and then define the probability for this pair based on this constraining target alone.

The cumulative distributions shown in Figs. 3 and 5 are visible in Fig. 6 as well. The two s-curves that describe the individual targets completely define the shape of this combined graph by following at each data point the s-curve that gives a lower probability for reaching the individual target. It is clear that, in general, mitigation is likely to improve the probabilities for reaching both targets, shown in Fig. 6 by the emergence of a larger high-probability surface area for reaching both targets. However, judging by our results it seems that full ‘when’ flexibility for mitigation causes the rate-of-change targets to be more difficult to reach, especially for a baseline with high initial emissions. This is, however, largely caused by our framing of the problem, which does not impose specific constraints concerning the rate of temperature change or timing of GHG emissions in general.

5. Mitigation technologies and costs

We next examine the relationship between mitigation costs and the probabilities of achieving the level and rate targets analyzed in Sections 3 and 4. First, we briefly discuss the nature of the mitigation options undertaken in these scenarios (also discussed more fully in this Special Issue [1]).

Scenario results indicate that a large portfolio of mitigation measures is necessary to achieve the respective targets. These comprise energy-related measures that range from energy conservation and efficiency improvements to structural changes of the energy system. These include shifts away from carbon-intensive coal to cleaner fuels (such as natural gas, renewables, and nuclear), as well as technologies that can be used as add-ons, which comprise mainly the capture of CO_2 during energy-conversion processes and subsequent storage in either geological formations or the ocean. Other important measures include changes in agricultural practices to reduce CH_4 and N_2O emissions, and enhancement of terrestrial sink activities in the forest sector. A comprehensive assessment of the mitigation portfolios of the scenarios is given in this Special Issue [1]. For reasons of comprehensiveness we illustrate in Fig. 7 the scenario’s resulting marginal abatement cost curves (MACs) of individual mitigation measures across all mitigation scenarios.[10] The figure illustrates the annual contribution of these measures as a function of GHG price for the time horizon 2000 to 2100. The zero-carbon options (including biomass, nuclear, other renewables, and carbon capture and storage) are among the reduction measures with the highest potential. In addition, significant mitigation is achieved through demand-side measures geared toward energy conservation and efficiency improvements as well as the reduction of CH_4 emissions. Other measures in the forestry sector (primarily sink enhancement), reductions of N_2O, and the mitigation of long-lived GHGs (F-gases) in the industry sector are seen to have comparatively limited mitigation potential.[11]

To assess the relationship between total costs and climate change outcomes, we measure costs as the cumulative undiscounted difference in GDP between the mitigation scenario and the baseline over the century, and compare these with the probability of achieving various targets. The relationship between costs and probabilities is not linear, since it depends on both the relationship between costs and emissions reductions (Fig. 7) as well as on the shape of the PDF for climate sensitivity. For example, Fig. 8 shows

---

[10] The MACs are not an exogenous input, but an endogenous result of our systems engineering model, which depicts competition between the alternative mitigation options on the level of individual technologies. Exceptions to this rule are CH_4 emissions reductions from rice cultivation and enteric fermentation, and N_2O from soil. For these sources we have applied regional MACs.

[11] The MACs of some of the mitigation options do not show the typical monotonic increase in deployment with increasing carbon prices. The reason for this behavior is competition between alternative measures. The relative economics of mitigation options is heavily influenced by the underlying price of carbon. For example, fossil carbon capture and storage (CCS) and nuclear in A2-670 (illustrated in Fig. 7) show decreasing contributions at carbon prices above 400 US$/tC. This results from additional inroads of demand-side measures (energy efficiency and conservation) and CCS from biomass energy conversion processes (Fig. 7) at relatively higher carbon prices.

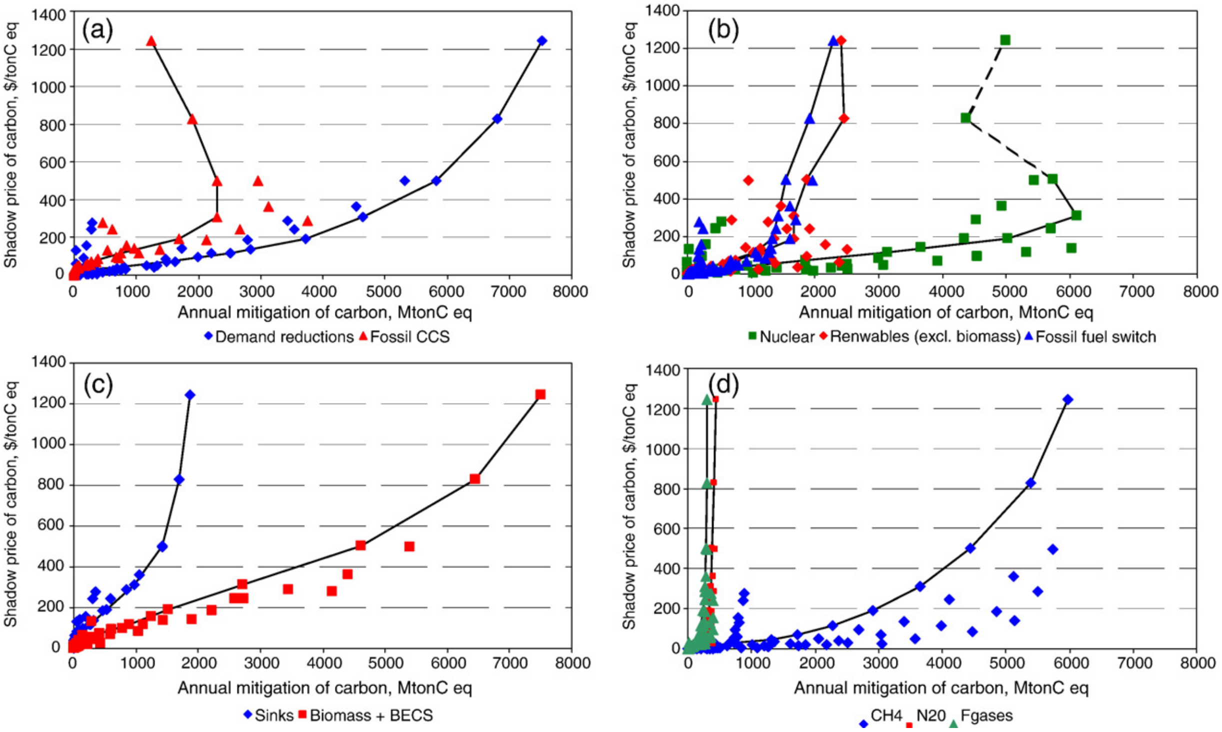

Fig. 7. Marginal abatement cost curves (MACs) for individual mitigation options. Dots denote the contribution of mitigation options across all A2r and B1 mitigation scenarios and decadal time steps (2000 to 2100). The black lines show the MAC for an illustrative scenario (A2r-670).

how the probability of reaching three different temperature-increase targets and three different rate-of-change targets changes as a function of cumulative undiscounted GDP losses, calculated as a percentage of the baseline GDP developments.

Fig. 8 shows that, although the probability of reaching a target depends on the PDF for climate sensitivity, the way in which probabilities change with increased mitigation costs is relatively robust across the two selected distributions. The probability increases approximately linearly for A2r scenarios, but for B1 the graph is more concave for all shown targets. That is, the initial mitigation investments in the B1 scenario have a large return in terms of increased likelihood of achieving targets (especially for higher targets), while additional investments show decreasing returns. This difference in dynamics is a result of differences in how far away from the target the unmitigated reference scenario lies. A2r has high emissions and therefore all the shown targets are very unlikely to be met without mitigation. Initial mitigation efforts have the lowest marginal costs, but also have little effect on the probabilities of achieving targets because those targets still lie in the tail of the distribution of the temperature-change outcomes. As reductions become deeper, marginal costs rise, but so too does the return in terms of increased probabilities of achieving targets, as the center of the projected temperature distribution moves closer to the target (see Fig. 3). The two effects roughly offset each other so that the risk–cost relationship is approximately linear.

In contrast, in B1 the probabilities for reaching the chosen targets are already much higher in the baseline and therefore the initial, relatively inexpensive mitigation efforts have a large return in terms of

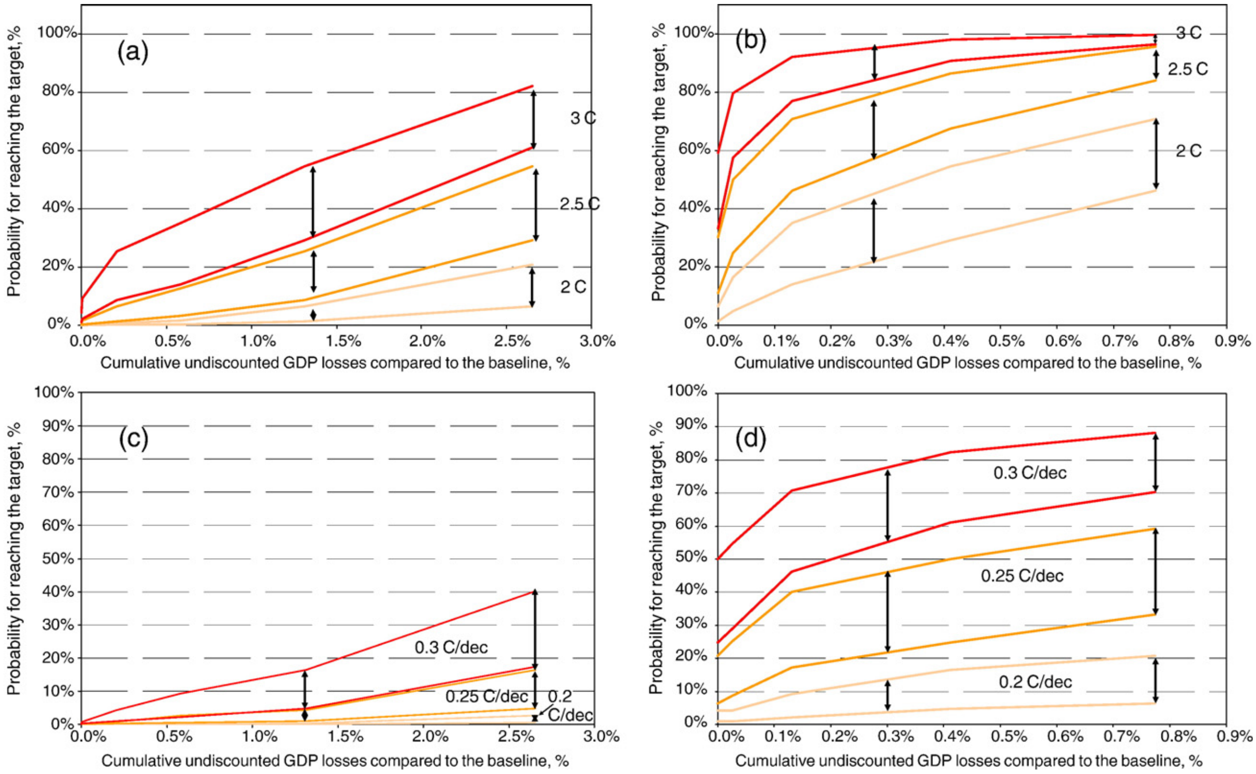

Fig. 8. Probability for reaching temperature (upper panels) and rate-of-change (lower panels) targets as a function of cumulative undiscounted GDP losses. A2r scenarios on the left and B1 scenarios on the right. The range of results for each target is bounded by the outcomes based on the AS [10] and WR [9] climate sensitivity PDFs. Note the different scales on the *x*-axis.

increased probability of achieving a target. Later, marginal costs rise and, as the likelihood of achieving targets climbs substantially above 50%, the additional probability gains diminish, so the risk–cost relationship begins to flatten.

In general, the observations for the rate-of-change targets and absolute temperature targets are similar. However, there are two general differences. First, rate-of-change targets are more difficult to achieve, especially in scenario A2r (also see Table 3). For example, the most stringent A2r mitigation scenario has a fairly high probability of reaching the higher absolute temperature-change targets, but still has a fairly low likelihood of achieving the rate-of-change targets. Second, for B1, the difference in likelihoods attributable to the choice of PDF is significantly larger for the rate targets than for the absolute temperature targets, especially for the higher targets (again, see Table 3 for more data).

The dynamics of the cost and probability increases for temperature-change targets are further explained with Fig. 9, which shows probability increases and the unit costs for these increases for all scenarios A2r and B1.

The left panels in Fig. 9 show for each mitigation scenario the increase in probability (given in %-units), relative to the baseline, for reaching any particular temperature target (targets shown on the *x*-axis). Further mitigation always increases the probability of reaching any given target, but the extent of this

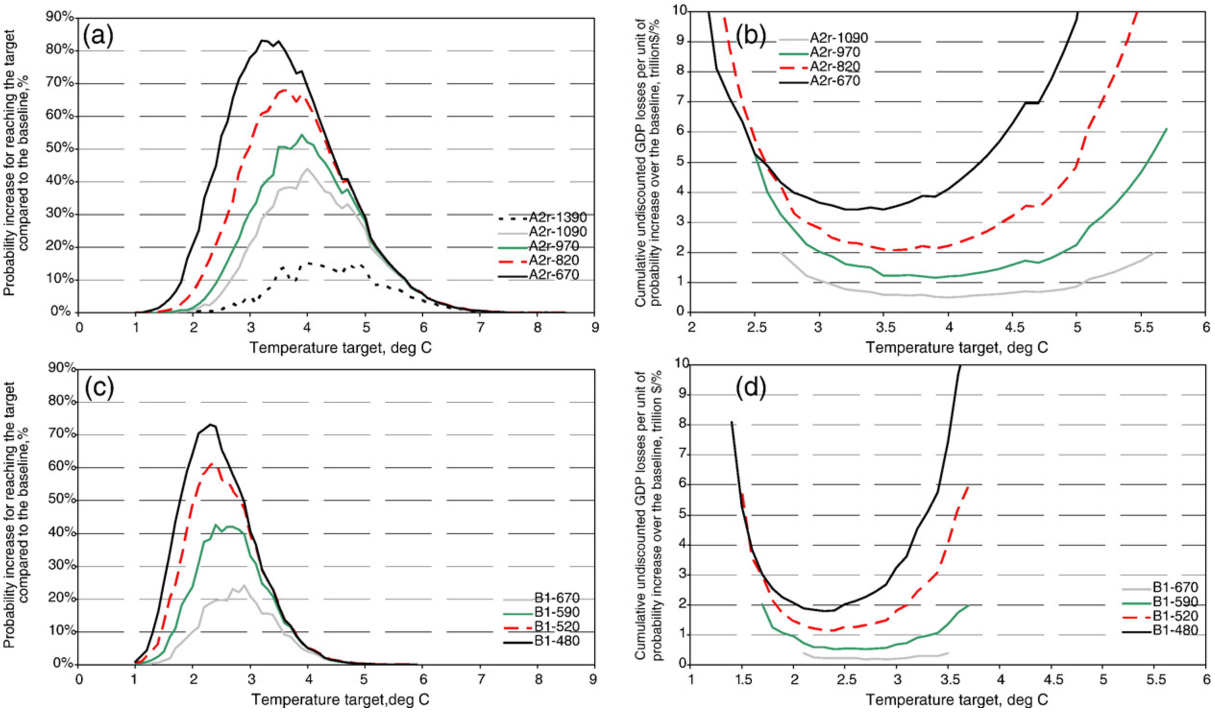

Fig. 9. The probability increases over the baseline (left panels) and the unit costs of these probability increases (right panels). WR PDF [9] used (curves produced with the PDF by AS [10] are similar, but located somewhat right of the curves shown here).

increase depends on the target considered. For example, the B1-670 scenario improves the chances of reaching a 3 °C target by more than 20%, while it improves the chances of reaching a 4 °C target by less than 5%. The peaks of the curves move left with stronger mitigation, which indicates that the largest probability gains shift to lower and lower targets as emissions reductions become deeper. The curves indicate for which temperature targets a particular mitigation scenario substantially improves the probability of achieving it. For example, if we require a probability increase of at least 10 percentage points (over the baseline probability) to define a mitigation scenario with a clear improvement over the baseline, scenario A2r-1090 qualifies for a range of targets from 2.7 °C to 5.6 °C, while scenario A2r-670 qualifies for targets between 1.9 °C and 5.7 °C. A larger required probability increase produces a smaller range of targets exhibiting clear improvement. This result shows that there is a range of mitigation scenarios that will make substantial progress, in probability terms, toward a certain temperature target, and going beyond this range is likely to be inefficient.[12] This inefficiency is visible in Fig. 8 when the slopes of the lines start to approach zero.

The right panels in Fig. 9 show the 'unit cost' for increasing the probability, based on the curves shown in the left panels. For the cost we have used the undiscounted GDP losses compared to the baseline.[13]

---

[12] This definition is, however, purely qualitative and the limit for the 'appropriate' increase depends on estimates from outside our modeling framework. The reason we use such a range for the cost indicators and the underlying assumption is that if increases less than 10% are accepted, the costs included in our model are not likely to be a deciding factor.

[13] Scenario A2r-1390 is excluded because its GDP losses are very close to zero.

These unit costs give some indication of how ‘cost-efficient’ it is to use a given mitigation scenario to reach a given target.[14] Combining the information from these figures with the ones in the left panels of Fig. 9 is often inconclusive; usually the lowest unit cost and the highest absolute probability increase are achieved with different mitigation scenarios.[15] In these cases, there are multiple preferable objectives (low unit cost and high absolute value for the probability increase) and the individual optima for these two objectives cannot be reached simultaneously. This means that, for cases like these, the choice always depends on how these two different objectives are weighted, what kind of risks the decision maker is willing to take to avoid additional costs from mitigation, and how these costs are weighed against the costs not included in our model (e.g., costs related to possible climate related damages). It is important that we have not included the ‘decision maker’ in our model (in terms of deciding which targets should be sought and what is the *value* of increasing the probability of reaching a target). We have merely produced indicators of mitigation costs and climate change that could be used together with other information to inform a decision process.

Fortunately, some more suggestive conclusions can also be drawn from Fig. 9. Based on our limited set of scenarios, it appears that below certain threshold for temperature targets, the most stringent mitigation scenarios do reach the optima for both of these objectives.[16] If a target lower than this threshold is set, the most stringent mitigation scenario available provides both the highest absolute probability increase and the lowest unit cost for this increase.

6. Implications of medium-term conditions for achieving climate change targets

Finally, we examine one specific aspect of the mitigation scenarios: the relationship between medium-term conditions at mid-century and long-term climate change outcomes. Several studies have highlighted the importance of medium-term (i.e., 2030–2060) outcomes to achieving long-term goals. For example, Hoffert et al. [37] argue that 10 TW of carbon-free power derived from radically new energy technologies is likely to be necessary by 2050 to make the stabilization of CO_2 possible. In contrast, Pacala and Socolow [38] argue that current technologies and measures deployed over the next 50 years would be sufficient to put the world on a course to eventual stabilization. O’Neill et al. [39] propose that international climate policy would benefit from the development of medium-term concentration targets as a way to keep open the option of achieving a range of long-term targets, as well as to limit rates of climate change of the next several decades. Several other studies have suggested other types of medium-term targets, and several individual countries have announced intentions to meet emissions targets for the middle of the century [39].

---

[14] For the cost indicators, we have used for all scenarios a required increase of 10%-units for the probability increase over the baseline probability for choosing the range of meaningful temperature targets that match each mitigation scenario. For the cases in which costs are not considered important, or in which costs outside those included in our modeling framework (e.g., damages caused by climate effects) dominate over those in the model, only probability increases (or absolute levels) matter and only the left panels of Fig. 9 are relevant (also see footnote 12).

[15] An extreme example of this is the baseline for which, without the 10% cutoff rule, we would have a cost indicator of zero for all targets (lowest cost), but also a value of zero for the probability increases (lowest increase).

[16] The most stringent mitigation scenarios are the only scenarios that can reach both of these optima; all the other scenarios have lower absolute probability increase for all targets.

However, no mitigation scenario analyses have explicitly analyzed the path dependency of outcomes by exploring what long-term climate change targets remain possible, and at what cost, conditional on the state of the world in the medium term (e.g., atmospheric concentrations, temperature change, technology portfolio, socio-economic conditions, etc.). Such an analysis requires multiple scenarios that explore the range of plausible long-term outcomes conditional on common medium-term characteristics. Although the mitigation scenarios described here are not of this nature — they generally differ in the medium term as well as in the long term — they can be used to take a first look at the relationships between mid-century conditions and long-term climate change goals.

For example, Figs. 10 and 11 show the relationships between the likelihood of remaining below 2 °C or 3 °C temperature-change targets and three measures of medium-term scenario characteristics: concentrations of equivalent CO_2, concentrations of true CO_2, and the zero-carbon share of the energy supply. They show that, in general, those characteristics with the longest timescales of change show the strongest links between medium-term and long-term outcomes. For example, there is only a weak relationship between equivalent CO_2 levels in 2050 and the likelihood of remaining below temperature change targets. For the 2 °C target, probabilities can be broadly described as medium likelihood (about 30–70%) for scenarios below 570 ppm, and low likelihood (generally less than 20%) for scenarios above 570 ppm. For the 3 °C target, there is little discernible pattern: scenarios above 570 ppm have likelihoods of remaining below the target that range from zero to 90%.[17] Our results span only a very small range of medium-term concentrations, but are suggestive nonetheless. Equivalent CO_2 concentrations include the radiative forcing effects of short-lived gases and aerosols (in addition to the effect of true CO_2). Therefore, although concentrations in 2050 are good predictors of climate change experienced over the first half of the century [4], they are not necessarily good predictors of concentrations in 2100, and therefore of long-term climate change outcomes. Equivalent CO_2 concentrations later in the century *are*, however, a good predictor of long-term climate outcomes, as evidenced by the strong correlation between concentrations in 2100 and the likelihood of achieving the targets (see upper right panel of Fig. 10).

In contrast, the concentration of true CO_2 in 2050 is much more clearly related to long-term outcomes, as would be expected given its long atmospheric lifetime and important effect on radiative forcing. For example, Fig. 10 shows that scenarios that achieve the 2 °C or 3 °C targets with 50% confidence have mid-century CO_2 concentrations of 430–460 and 510–530 ppm, respectively. This suggests that if CO_2 concentrations are substantially above these levels in 2050, achieving the associated climate change targets could only be done at costs substantially greater than the least-cost solutions derived here.

Fig. 11 shows the relationship between the share of zero-carbon energy supply in the scenarios and the probability of meeting the 2 °C and 3 °C temperature targets. This metric of the structure of the energy system can be thought of as an indicator for the decarbonization of the presently fossil-dominated energy system, and total quantities of zero-carbon energy supply that may be needed by 2050 have been used as a measure of the technological challenge presented by the climate change issue [37]. The timing of the introduction of these technologies and their absolute levels of deployment depends strongly on the assumed stringency of the mitigation regime and the socio-economic, demographic, and technology assumptions in the reference case.

---

[17] Most of the more stringent B1 mitigation scenarios peak in terms of CO_2-equivalent concentrations fairly soon after 2050 and they therefore have clearly lower concentrations in 2100 than in 2050.

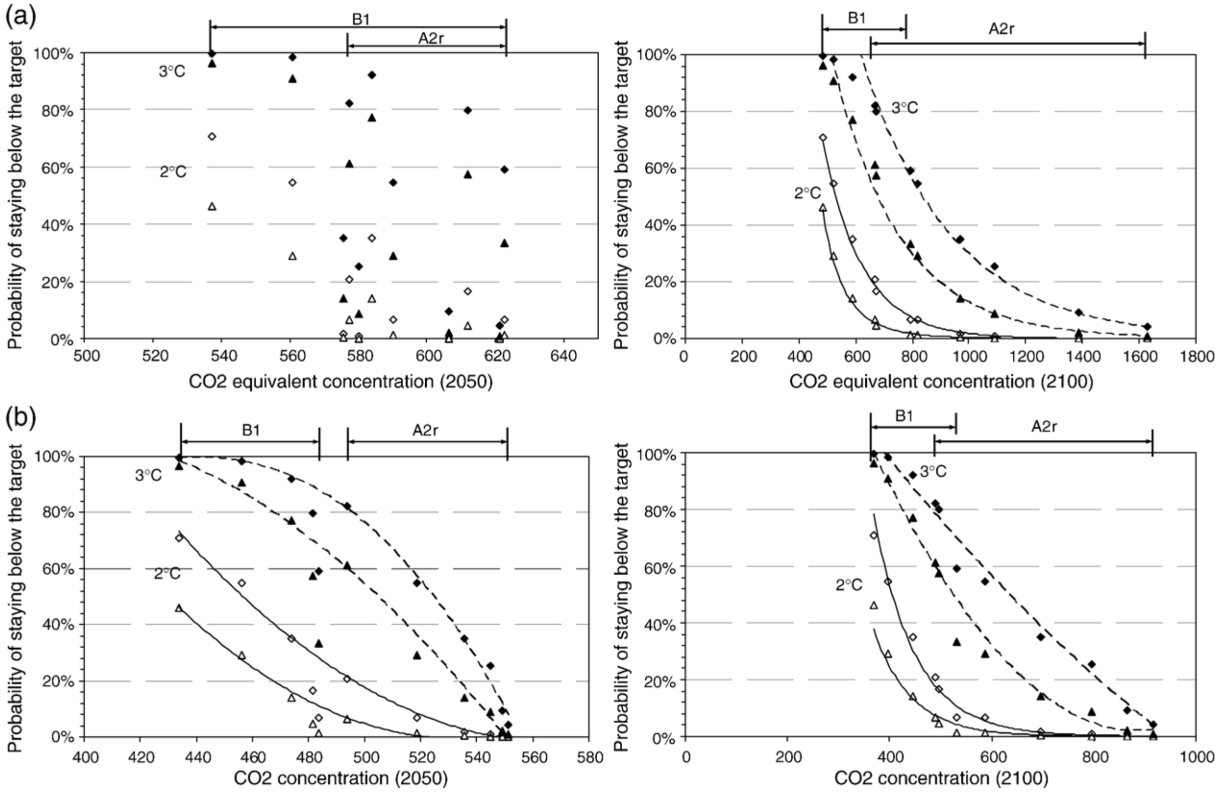

Fig. 10. Relationship between the probability of long-term temperature targets and (a) CO_2-equivalent concentrations (upper panels), and (b) CO_2 concentrations (lower panels). Black symbols give the probability for the 3 °C target and white symbols for the 2 °C target. Different symbols denote alternative PDFs (triangles, AS [10]; squares, WR [9]). Arrows show the range of the corresponding A2r and B1 scenarios.

Generally, more stringent stabilization scenarios require more rapid and widespread introduction of these technologies. In addition, we find that high rates of economic and technological development, as depicted by B1, lead to comparatively faster adoption of zero-carbon technologies compared with the fossil-intensive A2r baseline scenario (which is characterized by heavy reliance on fossil energy use throughout the century).

The left-hand panels of Fig. 11 clearly illustrate the correlation between the probability of achieving long-term temperature targets and the introduction of zero-carbon energy sources for the medium term (by 2050). A comparison with the right-hand panel, however, shows that this correlation does not exist for the long term. In fact, the majority of mitigation scenarios depict similar zero-carbon shares by 2100 with vastly different implications for the likelihood of meeting the 2 °C and 3 °C targets. Both the strong correlation over the medium term and the similarity of a large number of scenarios over the long term lead us to two important qualitative conclusions. First, we find that major *long-term* structural changes in the energy system are a necessary but not sufficient prerequisite to attain high likelihoods of 2 °C and 3 °C temperature outcomes. Second, the results point out that the decisive difference between the scenarios in terms of the likelihood of achieving long-term targets is the pace at which zero-carbon energy is introduced over the *short-to-medium term*.

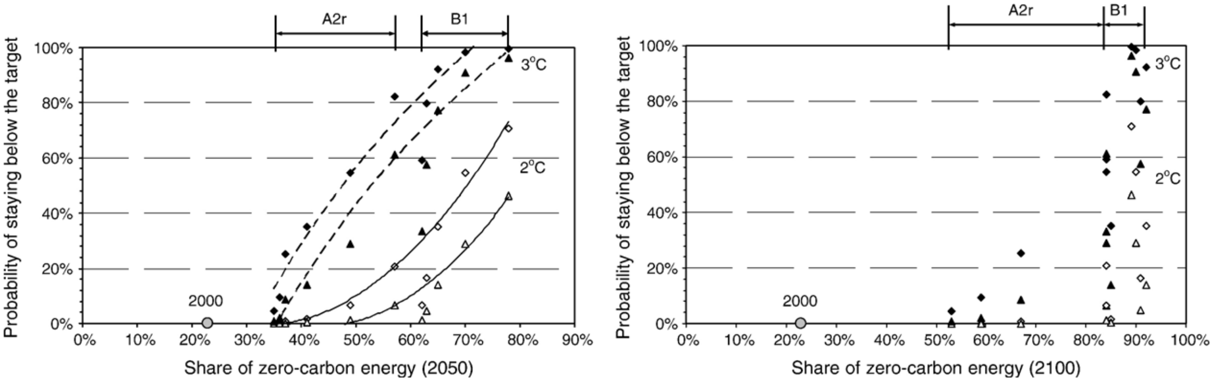

Fig. 11. Relationship between the probability of long-term temperature targets and the share of zero-carbon energy. Black symbols give the probability for the 3 °C target and white symbols for the 2 °C target. Different symbols denote alternative PDFs (triangles, AS [10]; squares, WR [9]). Arrows show the range of the corresponding A2r and B1 scenarios.

In a quantitative sense our scenario analysis suggests a very rapid increase of zero-carbon energy supply over the next five decades. For example, scenarios that meet the 2 °C and 3 °C targets with a likelihood above 50% depict an increase of zero-carbon shares by at least a factor of three and two, respectively. This corresponds to an increase in the global share of zero-carbon energy to more than 70% for the 2 °C target and more than 50% for the 3 °C target (by 2050, compared with today's share of about 22% [40]).[18] These results are also mirrored by the scenario's 'true' CO_2 concentrations by mid-century, which stay below 460 and 530 ppm, respectively, to meet the same targets with a probability of at least 50%. For the long term, all the scenarios with probabilities of above 50% foresee an increase in the share of zero-carbon energy to more than 80%.[19]

We emphasize that our analysis does not explicitly address the path dependency of outcomes by exploring what long-term climate change targets remain possible, and at what cost, conditional on the state of the world in the medium term. In that sense, our scenarios address what short-term response is needed to increase the probability of attaining various long-term climate change outcomes from a *cost-efficiency perspective*. They do not, however, address the issue of what long-term probability can be attained given specific interim targets. To address this issue requires the development of additional scenarios and the performance of sensitivity analysis with explicit consideration of the interim targets.

---

[18] Zero-carbon shares are calculated on the level of primary energy use, employing the substitution equivalent method, and assuming an efficiency of 33% for non-biomass renewable energy and nuclear, which, along with biomass, are assumed to be emissions free. In addition, we account fossil fuels for which carbon capture and storage is employed as zero-carbon. The share of fossil fuels considered zero-carbon is calculated based on the share of emissions captured of the total emissions that would have been emitted without the capture technologies.

[19] In addition to zero-carbon energy supply, options to reduce CO_2 emissions also include demand-side measures, fossil fuel shifts (away from coal to less-carbon intensive fossil fuels), forest sink enhancement, and the application of biomass-based carbon capture and storage. The contributions of these measures have an impact on the long-term 'true' CO_2 concentration levels, particularly in the low mitigation scenarios. This, together with the difference in the temporal nature of CO_2 concentrations and zero carbon shares, also explains the lack of relationship in the right-hand panels of Fig. 11 compared with Fig. 10(b).

7. Conclusions

In this paper we analyze the probabilistic climate change implications of a set of reference and mitigation scenarios. We find that the likelihood of staying below temperature-increase targets strongly depends on the underlying socio-economic developments in the reference scenario. If temperature targets are set low, these favorable baseline developments might even be necessary to reach these targets. At the same time, we conclude that mitigation measures are important as well: reducing emissions not only increases the probability of meeting temperature targets, but also reduces the uncertainty concerning future warming. Taken together, these conclusions suggest that achieving relatively low targets might require policies that extend beyond direct mitigation measures to those that influence broader development pathways (i.e., all the drivers that lead to a B1 world instead of an A2r one).

We also find that targets based on the rate of expected temperature change might very well prove to be more difficult to achieve, especially if full 'when' flexibility in mitigation is allowed and the baseline scenario developments favor a carbon-intensive world. A lack of explicit targets concerning the rate of temperature change or emission paths might lead to situations in which an absolute temperature-increase target is not breached, but the rate of temperature change is so fast that adaptation difficulties are experienced. We also find that two scenarios with similar probabilities of reaching an absolute temperature target can differ in their likelihood of exceeding a rate target. One reason this can happen is that they may assume different baseline scenarios, one in which emissions would otherwise grow quickly (e.g., with a carbon-intensive energy system), and one in which they would grow more slowly. These differences can lead to differences in least-cost mitigation paths, and different outcomes for rates of change in the mitigation scenarios. Another reason is that differences in mitigation strategies across scenarios can lead to differences in sulfur emissions, which can affect the rates of temperature change over short periods of time.

Our analysis also shows that the costs of mitigation and the way in which the mitigation affects the likelihood of achieving particular temperature targets is scenario dependent. For example, the probability of staying below a specific target is seen to increase roughly linearly with costs in the A2r scenario. In contrast, in B1, the initial mitigation costs have a substantially larger return in terms of likelihood than additional mitigation does. This outcome suggests that the role of socio-economic and technological development paths can be doubly important, not only affecting the overall costs of meeting a particular emissions reduction target, but also affecting the benefits of mitigation in terms of the increase in confidence of meeting climate change goals.

We show that for a given temperature target, there is a particular range of mitigation scenarios that will produce substantial increases in the probability of achieving it. Smaller reductions make little difference, and larger reductions make little further difference, to the chance of success. Conversely, for a given emissions mitigation scenario, there is a range of temperature targets for which the probability of achieving them increases substantially. We furthermore show that mitigation scenarios that produce the largest absolute probability gains usually have the highest cost per unit of probability increase. However, it appears that below a certain temperature target threshold the most stringent scenario available may have the attractive feature of coming at the lowest cost per unit of probability increase, even while producing the largest probability gains. Naturally our analysis concerns only mitigation costs, while decisions will be informed by damage costs estimates and other factors as well.

Our analysis of the mid-century conditions depicted by scenarios shows that climatically important characteristics with long timescales of change may be good indicators of temperature outcomes by the end of the century. Although, for our scenarios, the relationship between medium-term equivalent CO_2

concentrations and long-term temperature change is weak, mid-century true-CO_2 concentrations are a better predictor. Similarly, we find that the chances of meeting a particular long-term temperature target cost-efficiently is strongly related to the pace at which zero-carbon energy is introduced over the next five decades. Although these findings must be considered preliminary given the limited number of scenarios analyzed, they emphasize the importance of short-to-medium-term measures as part of a long-term cost-effective climate abatement strategy and suggest that interim targets could be an effective means of keeping long-term target options open over the next several decades.

As to the optimal technology portfolios for climate mitigation, we find that in the long term fundamental structural changes of the presently fossil-dominated energy system are a necessary, but not sufficient, condition to achieve low climate change outcomes. Meeting low temperature targets cost-effectively and at relatively high probabilities requires a wider portfolio of measures, including energy conservation and efficiency improvements, as well as mitigation options in the industry, agriculture and forest sectors.

Acknowledgments

We gratefully acknowledge Peter Kolp for programming assistance and Hal Turton for his valuable comments. We would also like to thank the two anonymous reviewers, whose comments were of great value in helping us to improve the quality and clarity of the paper. We acknowledge also the support by the Greenhouse Gas Initiative (GGI) project, an institute-wide collaborative effort within IIASA. The interdisciplinary research effort within GGI links all the major research programs of IIASA that deal with research areas related to climate change, including population, energy, technology, forestry, and land-use changes and agriculture. GGI's research includes both basic and applied, policy-relevant research aimed to assess conditions, uncertainties, impacts, and policy frameworks for addressing climate stabilization, from both near-term and long-term perspectives.

References

[1] K. Riahi, A. Gruebler, N. Nakićenović, Scenarios of long-term socio-economic and environmental development under climate stabilization, Technol. Forecast. Soc. Change (2006), doi:10.1016/j.techfore.2006.05.026.

[2] C. Azar, H. Rodhe, Targets for stabilization of atmospheric CO_2, Science 276 (5320) (1997) 1818–1819.

[3] B.C. O'Neill, M. Oppenheimer, Dangerous climate impacts and the Kyoto Protocol, Science 296 (5575) (2002) 1971–1972.

[4] B.C. O'Neill, M. Oppenheimer, Climate change impacts are sensitive to the concentration stabilization path, Proc. Natl. Acad. Sci. U.S.A. 101 (47) (2004) 16411–16416.

[5] M. Mastrandrea, S. Schneider, Probabilistic integrated assessment of 'dangerous' climate change, Science 304 (5670) (2004) 571–575.

[6] J. Hansen, Defusing the global warming time bomb, Sci. Am. 290 (3) (2004) 68–77.

[7] J. Corfee-Morlot, N. Höhne, Climate change: long-term targets and short-term commitments, Glob. Environ. Change 13 (4) (2003) 277–293.

[8] S. Hitz, J. Smith, Estimating global impacts from climate change, Glob. Environ. Change 14 (3) (2004) 201–218.

[9] T.M.L. Wigley, S.C.B. Raper, Interpretation of high projections for global-mean warming, Science 293 (5529) (2001) 451–454.

[10] N.G. Andronova, M.E. Schlesinger, Objective estimation of the probability density function for climate sensitivity, J. Geophys. Res., D: Atmos. 106 (D19) (2001) 22605–22611.

[11] J.M. Murphy, D.M.H. Sexton, D.N. Barnett, G.S. Jones, M.J. Webb, M. Collins, D.A. Stainforth, Quantification of modelling uncertainties in a large ensemble of climate change simulations, Nature 430 (7001) (2004) 768–772.

[12] J.M. Gregory, R.J. Stouffer, S.C.B. Raper, P.A. Stott, N.A. Rayner, An observationally based estimate of the climate sensitivity, J. Clim. 15 (22) (2002) 3117–3121.

[13] R. Knutti, T.F. Stocker, F. Joos, G.-K. Plattner, Probabilistic climate change projections using neural networks, Clim. Dyn. 21 (3–4) (2003) 257–272.

[14] N. Nakicenovic, P. Kolp, K. Riahi, M. Kainuma, T. Hanaoka, Assessment of emissions scenarios revisited, Environ. Econ. Policy Stud. 7 (3) (2006) 137–173.

[15] D. Rokityanskiy, B. Benitez, F. Kraxner, I. McCallum, M. Obersteiner, E. Rametsteiner, Y. Yamagata, Geographically explicit global modeling of land-use change, carbon sequestration and biomass supply, Technol. Forecast. Soc. Change (2006), doi:10.1016/j.techfore.2006.05.022.

[16] F.N. Tubiello, G. Fischer, Reducing climate change impacts on agriculture: global and regional effects of mitigation 1990 to 2080, Forecast. Soc. Change (2006), doi:10.1016/j.techfore.2006.05.027.

[17] S. Rao, K. Riahi, The role of non-CO_2 greenhouse gases in climate change mitigation: long-term scenarios for the 21st century, Energy Int. J. (in press).

[18] S. Messner, L. Schrattenholzer, MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively, Energy Int. J. 25 (3) (2000) 267–282.

[19] S. Messner, M. Strubegger, User's Guide for MESSAGE III. WP-95-69, IIASA, Laxenburg, 1995.

[20] A. Manne, R. Richels, Buying Greenhouse Insurance: the Economic Costs of CO_2 Emissions Limits, MIT Press, Cambridge, 1992, p. 194.

[21] B.J. DeAngelo, F.C. de la Chesnaye, R.H. Beach, A.Sommer, B.C. Murray, Methane and nitrous oxide mitigation in agriculture, Energy Int. J. (in press).

[22] T.M.L. Wigley, MAGICC/SCENGEN 4.1. Technical Manual, National Center for Atmospheric Research, CO, 2003.

[23] M. Meinshausen, What does a 2 °C target mean for greenhouse gas concentrations? A brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates, in: H.J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley, G. Yohe (Eds.), Avoiding Dangerous Climate Change, Cambridge University Press, New York, 2006.

[24] B. Hare, M. Meinshausen, How much Warming are we Committed to and How Much Can be Avoided? PIK Report, vol. 93, Potsdam Institute for Climate Impact Research, 2004 (http://www.pik-potsdam.de/publications/pik_reports).

[25] R.G. Richels, A.S. Manne, T.M.L. Wigley, Moving Beyond Concentrations: the Challenge of Limiting Temperature Change, AEI-Brookings Joint Center Working Paper, vol. 04-011, 2004 (http://www.aei-brookings.org/publications/abstract.php?pid=735).

[26] M. Webster, C. Forest, J. Reilly, M. Babiker, D. Kicklighter, M. Mayer, R. Prinn, M. Sarofim, A. Sokolov, P. Stone, C. Wang, Uncertainty analysis of climate change and policy response, Clim. Change 61 (3) (2003) 295–320.

[27] G. Yohe, N. Andranova, M. Schlesinger, To hedge or not against an uncertain climate future? Science 306 (5695) (2004) 416–417.

[28] T.M.L. Wigley, Choosing a stabilization target for CO_2, Clim. Change 67 (1) (2004) 1–11.

[29] S.H. Schneider, M.D. Mastrandrea, Probabilistic assessment of 'dangerous' climate change and emission pathways, Proc. Natl. Acad. Sci. U.S.A. 102 (44) (2005) 15728–15735.

[30] M. den Elzen, M. Meinshausen, Multi-gas emission pathways for meeting the EU 2 °C climate target, in: H.J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley, G. Yohe (Eds.), Avoiding Dangerous Climate Change, Cambridge University Press, New York, 2006.

[31] IPCC, Climate Change 2001: the Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001.

[32] IPCC, Climate change 2001: mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001.

[33] W. Hare, Assessment of Knowledge on Impacts of Climate Change — Contribution to the Specification of Art. 2 of the UNFCCC, Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU), Berlin, 2003.

[34] P.D. Jones, D.E. Parker, T.J. Osborn, K.R. Briffa, Global and hemispheric temperature anomalies — land and marine instrumental records, Trends: a Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN, 2005.

[35] F. Toth, Climate policy in light of climate science: the ICLIPS Project, Clim. Change 56 (1–2) (2003) 7–36.

[36] R. Swart, M.M. Berk, M.A. Janssen, G.J.J. Kreileman, R. Leemans, The Safe landing approach: risks and trade-offs in climate change, in: J. Alcamo, R. Leemans, G.J.J. Kreileman (Eds.), Global Change Scenarios of the 21st Century — Results From the IMAGE 2.1 Model, Elsevier Science, London, 1998, pp. 193–218.

[37] M.I. Hoffert, K. Caldeira, G. Benford, D.R. Criswell, C. Green, H. Herzog, A.K. Jain, H.S. Kheshgi, K.S. Lackner, J.S. Lewis, H.D. Lightfoot, W. Manheimer, J.C. Mankins, M.E. Mauel, L.J. Perkins, M.E. Schlesinger, T. Volk, T.M.L. Wigley, Advanced technology paths to global climate stability: energy for a greenhouse planet, Science 298 (5595) (2002) 981–987.

[38] S. Pacala, R. Socolow, Stabilization wedges: solving the climate problem for the next 50 years with current technologies, Science 305 (5686) (2004) 968–972.
[39] B.C. O'Neill, M. Oppenheimer, A. Petsonk, Interim concentration targets and the climate regime, Clim. Policy 5 (6) (2006) 639–645.
[40] IEA (International Energy Agency), World Energy Statistics 2005, IEA Publications, France, 2005.

Ilkka Keppo is a Research Scholar at the International Institute for Applied Systems Analysis in Laxenburg, Austria. He has been affiliated with the institute since 2004. His research interests include modeling and techno-economic analyses of energy systems and the components of these systems.

Brian O'Neill is the Leader of the Population and Climate Change (PCC) Program and a co-Leader of the Greenhouse Gas Initiative at the International Institute for Applied Systems Analysis, Austria, and an Associate Professor (Research) at the Watson Institute for International Studies at Brown University, USA (currently on leave). He holds a Ph.D. in Earth Systems Science and an M.S. in Applied Science, both from New York University.

Keywan Riahi is the Scientific Coordinator of the Greenhouse Gas Initiative (GGI) and Research Scholar in the Transitions to New Technologies Program (TNT) at the International Institute for Applied Systems Analysis (IIASA), Austria. His main research interests are the long-term patterns of technological change and economic development and, in particular, the evolution of the energy system.