Mitigating climate change through reductions in greenhouse gas emissions: is it possible to limit global warming to no more than 1.5°C?

Nicola Ranger, Laila Gohar, Jason Lowe, Alex Bowen and Robert Ward

Policy brief
August 2010

Grantham Research Institute on Climate Change and the Environment

Centre for Climate Change Economics and Policy

Met Office Hadley Centre

The Grantham Foundation for the Protection of the Environment

E·S·R·C Economic & Social Research Council

LSE The London School of Economics and Political Science

University of Leeds

Grantham Research Institute on
Climate Change and
the Environment

The Grantham Research Institute on Climate Change and the Environment was established in 2008 at the London School of Economics and Political Science. The Institute brings together international expertise on economics, as well as finance, geography, the environment, international development and political economy to establish a world-leading centre for policy-relevant research, teaching and training in climate change and the environment. It is funded by the Grantham Foundation for the Protection of the Environment, which also funds the Grantham Institute for Climate Change at Imperial College London. More information about the Grantham Research Institute can be found at: **http://www.lse.ac.uk/grantham**

Centre for
Climate Change
Economics and Policy

The Centre for Climate Change Economics and Policy was established in 2008 to advance public and private action on climate change through rigorous, innovative research. The Centre is hosted jointly by the University of Leeds and the London School of Economics and Political Science. It is funded by the UK Economic and Social Research Council and Munich Re. More information about the Centre can be found at: **http://www.cccep.ac.uk**

Met Office
Hadley Centre

The Met Office is a Government Trading Fund agency owned by the Ministry of Defence (MOD). It is the UK's Public Weather Service, providing the essential meteorological information that is used in public weather forecasts. The Met Office operates as a National Severe Weather Warning Service (NSWWS); and as one of only two designated World Area Forecast Centres providing worldwide weather forecast advice to the aviation industry. The Met Office employs more than 1,800 staff in offices around the world. The Met Office has vast experience in world class climate research which it has carried out for more than a quarter of a century. The Met Office Hadley Centre, set up in 1990, is the UK's official centre for climate research, and is acknowledged internationally as world leading. The scientific research carried out is under a directed policy-focussed programme. This programme is designed to provide the scientific basis that is required to help UK government policymakers and other stakeholders in the UK and internationally (including commercial customers and the public) deal with climate change in the future and make better informed decisions. More information about the Met Office can be found at: **http://www.metoffice.gov.uk**

Contents

Executive Summary

The Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are contemplating a range of goals for limiting the rise in global average temperature that is resulting from rising concentrations of greenhouse gases in the atmosphere. Whatever temperature goal is eventually agreed by the Parties, its achievement will depend on the extent to which global emissions of greenhouse gases can be limited and reduced.

We have carried out a study that explores a variety of potential paths for annual global emissions of greenhouse gases which would offer a reasonable chance of limiting a rise in global average temperature to no more than 1.5°C above its pre-industrial level.

As a first test, we explored simplified paths in which global emissions would be reduced to zero in 2021 and would remain at that level afterwards. This first test indicated that it would be very challenging to avoid a rise in global average temperature of more than 1.5°C. **Even if global emissions fall from 47 billion tonnes of carbon-dioxide-equivalent in 2010 to 40 billion tonnes in 2020, and are then reduced to zero immediately afterwards, we estimate that there would be a maximum probability of less than 50 per cent of avoiding global warming of more than 1.5°C above the pre-industrial level.**

However, if global emissions fall to less than 48 billion tonnes of carbon-dioxide-equivalent in 2020 and then are reduced to zero immediately afterwards, there would be at least about a 90 per cent chance that the global temperature would overshoot but return to within 1.5°C of the pre-industrial level within 50 years. **Therefore, if the global average temperature exceeds a rise of 1.5°C, it is possible that, after overshooting, it could fall back to the temperature goal over several decades if global annual emissions are reduced rapidly enough.**

These first tests were not intended to be realistic scenarios, as reducing emissions to zero in the next decade would have enormous economic cost, but provide an indication of whether a goal of avoiding a temperature rise of more than 1.5°C could be theoretically achieved.

We have also explored emissions paths corresponding to more plausible rates of decline in annual emissions after 2020, instead of assuming zero emissions. We have analysed two sets of emissions paths, each of which used different assumptions about the emissions baselines to 2020 and the amount of anthropogenic emissions of sulphate aerosols. **In all of these cases, the probability of avoiding a rise of more than 1.5°C above the pre-industrial level, without overshooting, was much less than 50 per cent.**

However, we have identified a number of emissions paths that offer a probability of 50 per cent of global average temperature being no more than 1.5°C above its pre-industrial level in the long term, but they involve temporarily overshooting the temperature goal for up to 100 years.

We have identified four key characteristics of emissions paths that offer at least 50 per cent probability of global average temperature being no more than 1.5°C above its pre-industrial level in the long term, with a temporary overshoot of no more than 100 years.

The first characteristic of the paths is that they involve early and strong reductions in global annual emissions. Our findings suggest annual global emissions must begin to fall within five years (by no later than 2015) and reach levels by 2020 of no more than 48 billion tonnes of carbon-dioxide-equivalent. A review of the literature indicates that such early and strong reductions in global annual emissions are likely to be feasible and economically desirable, if appropriate policy measures are put in place immediately to correct a range of market failures.

The second characteristic of the paths is that they require rapid reductions in annual global emissions after 2020. Our findings indicate that annual global emissions could need to fall at rates of at least around 3 per cent per year after 2020. Annual global emissions in 2020 of 44 billion tonnes or more of carbon-dioxide-equivalent would require reduction rates of at least 4 per cent per year afterwards. The feasibility of such rapid rates of emissions reductions is an area of active debate. We conclude that such rates could be technically feasible in certain circumstances, but are likely to entail considerably higher global costs than the 2°C goal, which would be reflected in higher global energy costs and lower world consumption than would be the case otherwise.

The third characteristic of the paths is that they require low annual global emissions by 2100, with a floor close to zero emissions in the long term. Annual global emissions would need to fall to much less than 5 billion tonnes of carbon-dioxide-equivalent by 2100. This may require the deployment of technologies (such as carbon capture and storage for biomass burning) that have 'negative net emissions' and could offset residual emissions in sectors such as agriculture where emissions reductions would be particularly difficult. It is not clear whether such technologies are feasible on the scale needed, nor whether they will be safe and reliable over long time horizons.

The final characteristic of the paths is that they are based on the assumption that it is possible for the global average temperature to exceed the goal (i.e. overshoot) and then return over the course of a few decades to no more than 1.5°C above the pre-industrial level. It is important to note that there are significant uncertainties associated with modelling overshoot scenarios. There is currently a scientific debate over how quickly atmospheric concentrations of greenhouse gases would decline following large reductions in emissions from human activities.

It is very important to recognise that overshooting any temperature goal would generate risks of triggering feedback accelerations, such as the enhanced release of carbon from the thawing of soils that are currently frozen, or causing large-scale and potentially dangerous impacts that could be difficult to reverse, such as a loss of species, inundation of some land areas, or extensive bleaching of corals. More research is needed into the likelihood of triggering feedbacks or irreversible impacts, such as large rises in sea level, during temporary overshooting of a 1.5°C goal.

Overall, our results do not rule out the achievement of a 1.5°C goal in the long term. Our findings suggest that, given historical trends in global annual emissions of greenhouse gases and, even with early and strong action to reduce emissions, the likelihood of avoiding global warming of more than 1.5°C above the pre-industrial level is low. However, it may be possible to limit the rise to no more than 1.5°C above the pre-industrial level in the long term, if the global average temperature is allowed to overshoot the goal and fall over a period of several decades.

Given the current uncertainties, one approach for policy-makers may be to take actions that will allow the option of switching at some later point to an emissions path that is consistent with a 1.5°C goal. Our analysis suggests that the range of global annual emissions of 40 to 48 billion tonnes of carbon-dioxide-equivalent in 2020, which would be consistent with a 2°C goal, might also be compatible with a 1.5°C goal, if it is assumed that emissions reductions could be quickly accelerated after 2020. Our findings suggest that aiming for the bottom end of this range for 2020 (i.e. taking strong action now) would reduce the risk of closing down the option of switching to a 1.5°C goal.

Mitigating climate change through reductions in greenhouse gas emissions: is it possible to limit global warming to no more than 1.5°C?

Nicola Ranger[1] , Laila Gohar[2] , Jason Lowe[2], Alex Bowen[1] and Robert Ward[1]

Introduction

The Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are contemplating a range of goals for limiting the rise in global average temperature that is resulting from rising concentrations of greenhouse gases in the atmosphere.

The Conference of the Parties, at its fifteenth session (COP15) in Copenhagen in December 2009, included a decision (UNFCCC 2010a) that "takes note" of the Copenhagen Accord. The Accord (UNFCCC 2010a) states:

"We underline that climate change is one of the greatest challenges of our time. We emphasise our strong political will to urgently combat climate change in accordance with the principle of common but differentiated responsibilities and respective capabilities. To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change. We recognize the critical impacts of climate change and the potential impacts of response measures on countries particularly vulnerable to its adverse effects and stress the need to establish a comprehensive adaptation programme including international support."

In addition to this recognition of a 2°C temperature goal, the Accord states:

"We call for an assessment of the implementation of this Accord to be completed by 2015, including in light of the Convention's ultimate objective. This would include consideration of strengthening the long-term goal referencing various matters presented by the science, including in relation to temperature rises of 1.5 degrees Celsius."

As of 22 July 2010, 114 Parties had agreed to the Accord, and a further 23 had expressed their intention to agree. However, the Copenhagen Accord and its 2°C temperature goal have not yet been adopted by all of the 194 Parties to the UNFCCC. Ahead of the eleventh session of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention, the chair published a note (UNFCCC 2010b) containing 'Text to facilitate negotiations among Parties'. In the first section on 'A shared vision for long-term cooperative action', the document states (including square brackets around optional text):

*"Agrees that…*Deep cuts in global emissions are required according to science, and as documented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, with a view to reducing global emissions so as to maintain the increase in global temperature below [1][1.5][2] degrees Celsius above pre-industrial levels, and that Parties should take action to meet this objective consistent with science and on the basis of equity[, taking into account historical responsibilities and equitable access to global atmospheric space]*."*

Whatever temperature goal is eventually agreed by the Parties to the UNFCCC, its achievement will depend on the extent to which global emissions of greenhouse gases can be limited and reduced. Bowen and Ranger (2009) (including the technical paper by Ranger *et al.*, 2009), described an analysis of paths for global emissions which would offer at least a 50 per cent chance of avoiding a rise in global average temperature of more than 2°C above its pre-industrial level. This document explores paths for global emissions that would offer a significant chance of limiting a rise in global average temperature to no more than 1.5°C above its pre-industrial level. It also considers the potential for achieving the 1.5°C goal by initially pursuing a path for a 2°C goal.

[1] Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London, UK.

[2] Met Office Hadley Centre, Exeter, UK.

Methodology

The climate modelling approach used in this study was identical to that of Ranger *et al*. (2009). The inputs to the model were emission paths. The outputs were probability distributions of global average near surface warming

The climate modelling was carried out by the Met Office Hadley Centre as part of the AVOID programme using a simple climate model (MAGICC; Wigley and Raper, 2001) set up to sample uncertainty in key climate system parameters (Lowe *et al.*, 2009). In particular, the model takes into account uncertainties in climate sensitivity, climate-carbon cycle feedback and ocean heat uptake. The model is tuned to replicate some aspects of the results from more complex climate and earth system models.

Another key uncertainty in the model is the size of the climate forcing by anthropogenic emissions of aerosols. We have used more than one set of aerosol assumptions in this study to highlight the effect of this particular uncertainty.

It is important to recognise that the simple model framework we have used here is one of several available, and each model can only provide an estimate of the future climate and the associated uncertainty. At present, the temperatures that are projected for emissions paths after a peak are particularly uncertain.

First test: achievement of a 1.5°C goal in post-2020 scenarios for zero emissions

We constructed simplified scenarios that represented a world in which global emissions would be theoretically reduced to zero in 2021 and would remain at that level afterwards. This was not intended to represent a realistic future scenario, but it was a useful ‘first test’ of the basic feasibility of a 1.5°C goal; for example, if it was found that there would be less than a 50 per cent chance of avoiding a warming of 1.5°C, even if emissions were reduced to zero after 2020, then a more realistic gradual reduction in emissions, consistent with current policy discussions, would not be able to achieve the goal either.

The emissions paths in this ‘first test’ followed the same ‘business as usual’ path to 2012 as is described in Ranger *et al*. (2009)[3] . Thereafter global emissions were assumed to fall to either 40 or 48 billion tonnes of carbon-dioxide-equivalent in 2020. These two levels represent the bounds of the ‘2°C envelope’ presented in Bowen and Ranger (2009) and discussed in Stern (2009). The upper bound was described as the approximate level above which it was considered potentially unfeasible to achieve a 50 per cent chance of avoiding warming of more than 2°C because rapid annual reductions (of greater than 4 per cent per year) of global emissions would be required. The lower bound marked the level below which unfeasible annual reductions in global emissions would be required between 2015 and 2020. The upper bound of 48 billion tonnes of carbon-dioxide-equivalent is close to the estimated level of annual global emissions in 2010 of 47 billion tonnes. This upper bound is also less than the collective sum of emissions limits and reductions that have been pledged so far by countries through the Copenhagen Accord (Taylor and Stern, 2010; Lowe *et al.*, 2010).

After 2020, global emissions of all greenhouse gases were assumed to fall to zero. Figure 1 shows the two emissions paths.

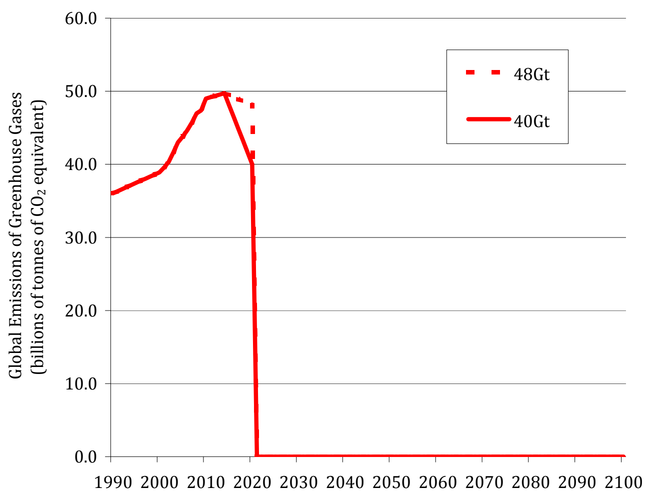

Figure 1: The ‘first test’ emissions paths.

The baseline assumption for anthropogenic aerosols was that their emissions evolved along a path that was directly related to the total emissions of carbon dioxide, using the ratio determined from the SRES A2 emissions scenario (as in the ‘upper’ aerosol scenario used in Ranger *et al.*, 2009). For comparison, we also produced an extra scenario for one case in which aerosols were fixed at their 2020 level - in this scenario, the level of aerosols was higher than in the other cases, and so was expected to lead to lower estimated increases in temperature.

[3] ‘Business as usual’ assumes global annual emissions of 47 billion tonnes of carbon-dioxide-equivalent in 2010, increasing to about 48 billion tonnes in 2012. Our estimates lie within the range of estimates published by other research groups.

Scenario	Peak temperature rise (°C)		Probability of remaining ≤ 1.5°C between 2000 and 2100	Probability of temperatures being ≤1.5°C, allowing an overshoot period less than:		
	50th percentile	90th percentile		50 years	100 years	200 years
2020 = 48 billion tonnes of carbon-dioxide-equivalent	1.5	1.9	45%[4]	90%	>90%	>90%
2020 = 40 billion tonnes of carbon-dioxide-equivalent	1.5	1.9	45%	90%	>90%	>90%
2020 = 48 billion tonnes of carbon-dioxide-equivalent, constant aerosol levels	1.2	1.4	>90%	>90%	>90%	>90%

Table 1: Estimated temperature increases (relative to the pre-industrial level) for the 'first test' emissions scenarios.

Table 1 provides a summary of the findings for the 'first test' emissions scenarios. Using the baseline aerosol assumption, the median projected warming was just over 1.5°C above the pre-industrial level for both paths, while the probability of remaining at or below 1.5°C was about 45 per cent. This indicates that there would be less than a 50 per cent chance of avoiding global warming of more than 1.5°C above the pre-industrial level if emissions are higher than 40 billion tonnes of carbon-dioxide-equivalent in 2020, even if annual emissions could be reduced to and maintained at zero immediately afterwards. In other words, it is not possible to achieve even a 50 per cent chance of avoiding warming of more than 1.5°C (i.e. not allowing temperature to overshoot the goal) if annual global emissions are between 40 and 48 billion tonnes of carbon-dioxide-equivalent in 2020, even with significant reductions after 2020.

However, the modelling results also showed that the temperature would eventually fall, even if it exceeded a rise of 1.5°C; we estimate that for these emissions paths there would be about 90 per cent chance or more that global average temperature would not remain higher than 1.5°C above its pre-industrial level for more than 50 years if the temperature goal was overshoot. The size of any overshoot of the temperature goal would probably be less than 0.5°C; Table 1 indicates that there would be around 90 per cent chance that the maximum temperature reached would be no more than 1.9°C above the pre-industrial level. In all cases, warming remained no higher than 2°C with a probability of more than 90 per cent.

It is important to note that there are significant uncertainties associated with modelling overshoot scenarios and the risks associated with the higher levels of peak warming that they imply. This issue is considered further in a later section.

As expected, the scenario in which aerosols were fixed at their 2020 level (i.e. a higher post-2020 level than in the baseline aerosol scenario) resulted in a significantly different probability of avoiding warming of more than 1.5°C. Under the assumption of fixed aerosol concentrations (a high aerosol assumption), the median estimate of peak warming was 1.2°C instead of just over 1.5°C, and the probability of achieving the 1.5°C goal was more than 90 per cent rather than 45 per cent. Such a scenario may be less realistic than the baseline scenario, given current trends in air pollution regulation; high levels of aerosols in the atmosphere can have significantly negative impacts on human health, ecosystems and infrastructure. Realising the conditions assumed in the scenario for fixed aerosol concentrations would probably require the application of geoengineering. At present there are many technical hurdles standing in the way of geoengineering on such a scale, as well as the risk of unexpected adverse consequences.

We have concluded that the model results for our 'first test' emissions scenarios do not rule out the achievement of a 1.5°C goal in the long term. If a temporary overshoot is allowed, these results suggest that a number of feasible post-2020 emissions paths could be compatible with this temperature goal.

[4] Here the probability of remaining at or below 1.5°C is 45 per cent, while the mean (50th percentile) warming is 1.5°C. The reason for this apparent discrepancy is that the median warming here is slightly above 1.5°C, but is 1.5°C when rounded to one decimal place in this table.

Achievement of a 1.5°C goal in post-2020 scenarios for gradual emissions reductions

In this section, we describe model results for paths corresponding to more plausible rates of decline in annual global emissions after 2020, instead of an immediate fall to zero. We analysed two sets of emissions paths, each of which explored different assumptions to allow a sensitivity test of our findings. The differences relate to assumptions about the emissions baselines up to 2020, the shape of the paths, and the amount of anthropogenic emissions of sulphate aerosols.

The first set of emissions paths was extracted from the database of 200+ results from the AVOID programme (www.avoid.uk.net). These were paths that showed an estimated median peak warming of less than or equal to 2°C (14 paths in total). This set of paths was reanalysed to assess the probability of exceeding a temperature rise of 1.5°C above the pre-industrial level. The specification and calculation of these paths is described in Gohar and Lowe (2010)[5] .

The analysis of the second set of emissions paths extended the results that were presented in Ranger *et al*. (2009) and discussed in Stern (2009). These paths explored the feasibility of switching paths in 2020 from a 2°C goal to a 1.5°C goal. Annual global emissions were assumed to follow a 'business as usual' path up to 2012[6] , before falling to 40, 44 or 48 billion tonnes of carbon-dioxide-equivalent in 2020 (Ranger *et al.*, 2009; Stern, 2009). Emissions were assumed to fall after 2020, reaching a constant annual rate of reduction of between 3 and 6 per cent per year. We examine in later sections the feasibility of such annual reduction rates. As in Ranger *et al*. (2009), each path used either an 'upper' or 'lower' scenario for anthropogenic emissions of aerosols. In both scenarios, aerosol emissions were assumed to fall significantly over time, but at different rates.

The paths for annual emissions of greenhouse gases are shown in Figure 2. For comparison, the figure includes the key paths presented in Ranger *et al.* (2009) which offered a 50 per cent chance of limiting warming to no more than 2°C above the pre-industrial level.

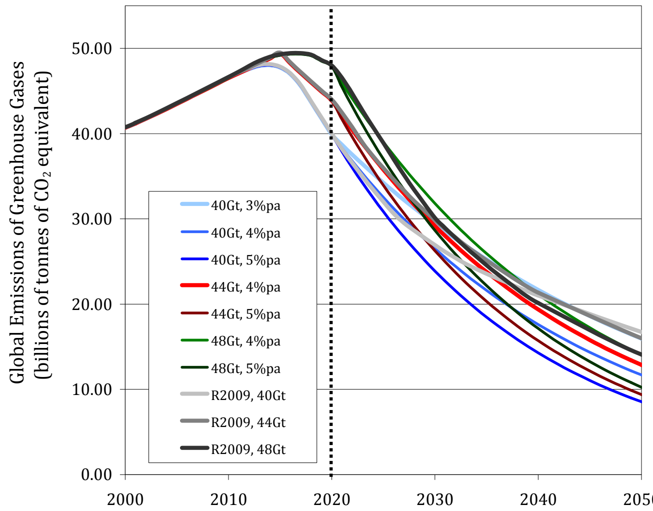

Figure 2: Baseline emissions paths (Gt = billions of tonnes). This includes three new sets of paths that reach 40 (blue), 44 (red) and 48 (green) billion tonnes of carbon-dioxide-equivalent in 2020. The figure also shows the emissions paths from Ranger et al. (2009) which reach 40, 44 and 48 billion tonnes of carbon-dioxide-equivalent in 2020 and which offer a 50 per cent chance of avoiding warming of more than 2°C (denoted R2009 in the legend).

There is an important difference between the two sets of emissions paths considered in this study and those presented in Ranger *et al.* (2009) in terms of the assumed contributions of emissions of the different greenhouse gases over time. In Ranger *et al.* (2009), carbon dioxide emissions were assumed to be mitigated more rapidly than emissions of other greenhouse gases, resulting in methane and nitrous oxide emissions constituting a higher proportion in 2100. But in this study, the proportions of different gases are assumed to follow the SRES A1B scenario, and consequently, carbon dioxide constitutes a larger proportion in 2100. It is debatable as to which scenario is more realistic. One implication of this difference in assumptions is that this study may be slightly more optimistic than Ranger *et al.* (2009) for emissions paths beyond 2020 (i.e. Ranger *et al.* (2009) would imply that lower levels of emissions, by a few billions of tonnes compared with this study, would be required to achieve the same temperature goal in 2050). The sensitivity of temperature to these assumptions will be explored in future work.

[5] Each path follows the SRES A1B 'business as usual' scenario up to the year of the emissions peak (i.e. slightly higher than in Ranger *et al.*, 2009); anthropogenic aerosol emissions are equivalent to the 'upper' aerosol scenario of Ranger *et al*. (2009); and the relative contributions of different greenhouse gases are assumed to evolve based on ratios taken from the SRES A1B scenario.

[6] As in Ranger *et al*. (2009); see footnote 3.

Table 2

Scenario (Yr_Rx_Fz)*	Annual reduction rate post-2020	Probability ≤ 1.5°C 2000-2100	Peak temperature rise (°C)		Probability of staying ≤1.5°C, allowing an overshoot period of:		
			50th	90th	<50 years	<100 years	<200 years
2016_R4_F0	4%	10%	1.9	2.8	25%	35%	60%
2016_R5_F0	5%	15%	1.9	2.6	30%	45%	65%
2016_R6_F0	6%	15%	1.8	2.6	35%	50%	70%
2020_R5_F0	5%	10%	2.0	2.9	20%	30%	55%
2020_R6_F0	6%	10%	2.0	2.8	20%	35%	60%
2014_R3_F0	3%	20%	1.8	2.7	35%	45%	65%
2014_R4_F0	4%	25%	1.7	2.5	45%	55%	75%
2014_R5_F0	5%	30%	1.7	2.4	55%	65%	80%
2014_R6_F0	6%	30%	1.6	2.3	60%	70%	85%
2014_R4_FL	4%	15%	2.0	3.3	25%	30%	35%
2014_R5_FL	5%	15%	1.9	3.2	30%	30%	40%
2014_R6_FL	6%	20%	1.9	3.1	35%	35%	40%
2016_R5_FL	5%	10%	2.0	3.3	25%	25%	30%
2016_R6_FL	6%	15%	1.9	3.2	25%	30%	35%

*Table 2: Emissions characteristics and temperature projections for the AVOID scenarios. The shading reflects the probability of falling below 1.5°C at different overshoot periods: orange corresponds to a probability of at least 50 per cent of falling to ≤1.5°C within 50 years of overshoot, yellow for 100 years, cream for 200 years, and red for more than 200 years. *The scenario name reflects the year in which global annual emissions reach their peak (Yp), the annual rate of emissions reductions after 2020 (x) and the emissions floor (z); denoted Yr_Rx_Fz.*

Table 3

Scenario	Emissions in 2020 (billions of tonnes of carbon-dioxide-equivalent)	Annual reduction rate post-2020	Emissions floor in 2100 (billions of tonnes of carbon-dioxide-equivalent)	Probability ≤ 1.5°C 2000-2100	Peak temperature rise (°C)		Probability of staying ≤1.5°C, allowing an overshoot period:		
					50th	90th	<50 years	<100 years	<200 years
40_3%	40	3%	3.4	20% [35%]	1.8 [1.6]	2.5 [2.3]	40% [65%]	60%	>90%
40_4%	40	4%	1.5	25% [45%]	1.7 [1.6]	2.3 [2.1]	60% [70%]	70%	>90%
40_5%	40	5%	0.7	35% [45%]	1.6 [1.5]	2.2 [2.1]	65% [75%]	80%	>90%
40_6%	40	6%	0.3	40% [45%]	1.6 [1.5]	2.1 [2.0]	75% [80%]	85%	>90%
44_4%	44	4%	1.6	20% [40%]	1.7 [1.6]	2.3 [2.2]	50% [65%]	65%	>90%
44_5%	44	5%	0.7	30% [40%]	1.7 [1.6]	2.2 [2.1]	60% [70%]	75%	>90%
44_6%	44	6%	0.3	35% [45%]	1.6 [1.5]	2.1 [2.1]	70% [75%]	80%	>90%
48_4%	48	4%	1.8	20% [30%]	1.8 [1.6]	2.4 [2.3]	45% [60%]	60%	>90%
48_5%	48	5%	0.8	25% [35%]	1.7 [1.6]	2.3 [2.2]	55% [65%]	70%	>90%
48_6%	48	6%	0.3	30% [40%]	1.7 [1.6]	2.2 [2.1]	65% [70%]	75%	>90%

Table 3: Emissions characteristics and temperature projections for the second set of scenarios (based on Ranger et al., 2009) assuming the lower aerosol scenario. Scenario names reflect emissions in 2020 and post-2020 reduction rates. Numbers in brackets are the equivalent estimates for the upper aerosol scenario. Row shading is as in Table 2.

Tables 2 and 3 present the findings for the two sets of emissions paths. Each of the paths offered at least 50 per cent chance of limiting warming to no more than 2°C above the pre-industrial level.

Table 2 shows the results for the emissions paths extracted from the AVOID results. Each path assumed a different year for a peak in global emissions (2014, 2016 or 2020), a different annual rate of emissions reductions (between 4 and 6 per cent per year) and a different emissions floor[7] (either zero or non-zero). All of these paths offered a significantly lower probability than 50 per cent of keeping temperatures below 1.5°C at all times, despite the fact that they assumed post-2020 rates of emissions reductions of 3 to 6 per cent annually. The median estimate of peak warming ranged from 1.8°C to 2°C above the pre-industrial level.

As with the 'first test' scenarios, these results show that global average temperatures slowly decline following their peak. Three of the 14 emissions paths provided a probability of more than 50 per cent of the temperature ending up at or below 1.5°C after an overshoot period of up to 100 years (for two paths the overshoot period was 50 years). These three paths each represent ambitious scenarios for reductions in emissions; all assumed early and rapid global emissions reductions, beginning in 2014 and then falling at rates of between 4 and 6 per cent per year after 2020. Importantly, each of these paths fell to a floor of zero emissions; that is, global emissions fell to less than about 4 billion tonnes of carbon-dioxide-equivalent by 2100 and reached zero over the long-term.

We have concluded from these results that a low emissions floor would be crucial to achieving a temperature goal of 1.5°C in the long term after overshooting. For example, those paths which followed the same early trajectory but ended with a non-zero long-term emissions floor offered less than 50 per cent chance of temperatures falling within 1.5°C of the pre-industrial level within 200 years of an overshoot.

The size of the emissions floor also appears to be important in constraining the peak temperature. For the '2014_R5_F0' and '2014_R5_FL' paths, which were identical except for the size of the emissions floor, the median projected peak temperature increase was, respectively, 1.9°C and 1.7°C, while the 90th percentile projection was 3.2°C and 2.4°C.

Table 3 shows the results for the paths that extended the analysis of Ranger *et al*. (2009). They lead to similar conclusions. Even for paths that involved ambitious annual reductions of emissions after 2020, overshooting 1.5°C was highly likely. However, for all of the paths in this set, there was greater than 50 per cent chance of falling to no more than 1.5°C above the pre-industrial level within less than 100 years after an overshoot, and for most paths, the overshoot lasted less than 50 years. These conclusions hold for both the upper and lower aerosol scenario.

Each of these paths assumed early and strong reductions, with global emissions falling to between 40 and 48 billion tonnes of carbon-dioxide-equivalent by 2020, followed by strong annual cuts of up to 6 per cent per year afterwards. Each path also assumed a floor of zero emissions, with the annual total falling to less than 3.5 billion tonnes of carbon-dioxide-equivalent by 2100. For paths involving an overshoot of less than 50 years, in the baseline (lower aerosol) scenario, annual emissions fell to no more than 1.5 billion tonnes of carbon-dioxide-equivalent by 2100.

Bowen and Ranger (2009) identified a number of emissions paths that offered a 50 per cent probability of avoiding a rise in global average temperature of more than 2°C. Those paths also offered a 5 per cent chance of avoiding a rise of more than 1.5°C. Table 3 provides information about the possibility of switching in 2020 from a path consistent with a 2°C goal to one having a reasonable chance of achieving a 1.5°C goal.

[7] The emissions floor is the minimum level of global annual emissions that is reached (usually after 2100).

For the baseline (lower aerosol) scenario, if emissions were at or below 44 billion tonnes of carbon-dioxide-equivalent in 2020, temperatures returned to 1.5°C or below within 50 years of the start of the overshoot, if annual emissions fell at a rate of 4 per cent per year or more after 2020. This indicates that there could be an option to strengthen a temperature target to 1.5°C in the coming decade, assuming that an annual rate of reduction in global annual emissions of 4 per cent per year after 2020 is feasible. The feasibility of such annual reductions is uncertain - stronger earlier cuts would be required to avoid the need to make such big reductions after 2020. For these paths, the median estimates of the projected peak temperature rise were about 0.1 to 0.2°C higher than the goal of 1.5°C.

These paths also showed that if global annual emissions were at around 48 billion tonnes of carbon-dioxide-equivalent in 2020, then a faster rate of emissions reductions of 5 per cent per year afterwards would be required to achieve a long-term goal of global average temperature being no more than 1.5°C higher than its pre-industrial level. The risks associated with this option are higher; for example the feasibility of sustained emissions reductions of 5 per cent per year is unclear and the probability of overshooting and reaching higher peak temperature increases would be greater.

Under the upper aerosol scenario (which we consider to be based on optimistic assumptions), a lower peak warming occurred, and the required annual reductions in global emissions were smaller.

We note that each of these paths required atmospheric concentrations of greenhouse gases to peak and fall to much lower levels than those discussed in Ranger *et al*. (2009). All of the paths resulted in peaks in atmospheric concentrations of between about 470 and 480 parts per million of carbon-dioxide-equivalent by 2025-2030, before falling back to below 375 parts per million by 2200.

The feasibility of emissions paths

We have identified four key characteristics of emissions paths that offer at least 50 per cent chance of limiting global average temperature to no more than 1.5°C above its pre-industrial level in the long term, with a temporary overshoot of no more than 100 years.

- *Early and strong reductions in global annual emissions:* our findings suggest that annual global emissions must begin to fall within five years (i.e. no later than 2015) and reach levels by 2020 of no more than 48 billion tonnes of carbon-dioxide-equivalent.
- *Rapid reductions in annual global emissions after 2020:* we estimate that annual global emissions could need to fall at rates of at least about 3 per cent per year after 2020 . Annual global emissions in 2020[8] of 44 billion tonnes or more of carbon-dioxide-equivalent would require reduction rates of at least 4 per cent per year afterwards.
- *Low annual global emissions by 2100 and a floor of zero emissions in the long term:* annual global emissions would need to fall to much less than 5 billion tonnes of carbon-dioxide-equivalent by 2100 and continue to fall to zero.
- *An assumption that it is possible return to a temperature goal of 1.5°C over many decades after overshooting.*

The feasibility of each of these characteristics is open to debate (some more so than others). If any were shown to be infeasible, then it might be impossible to achieve the 1.5°C goal during the next century, given where we are today. The following sections consider the feasibility of each of these characteristics.

Early and strong reductions in global annual emissions

The feasibility of early and strong reductions in annual emissions on this scale has been discussed extensively in the literature. Bowen and Ranger (2009) summarised the current evidence and concluded that early and strong reductions in global annual emissions are likely to be feasible and economically desirable, if appropriate policy measures are put in place immediately. In particular, there are a range of market failures the correction of which could generate substantial energy efficiency improvements, faster innovation and better coordination of infrastructure investment in the near term. These failures include problems such as inadequate provision of information about energy-saving opportunities, weak incentives for research and development, and disincentives to set up new networks for energy distribution or improve old ones. The resource costs of correcting these market failures need not be very high if policies are appropriately designed; indeed, action on this front may actually save money, as is evident from the abatement cost curves constructed by McKinsey & Company (2009). However, the very fact that these failures have continued to exist for a considerable time suggests that they may be difficult to overcome, so there is considerable uncertainty around the scope for early and cheap abatement.

Rapid reductions in annual global emissions after 2020

The speed of annual reductions in global emissions that are likely to be feasible after 2020 depends on many factors, including:

- the growth rates of global GDP;
- the fraction of GDP that can be invested in plant, equipment and buildings embodying technologies that are less greenhouse-gas-intensive;
- the time taken to plan, install and learn to operate new investment;
- the pace of energy efficiency improvements;
- the speed at which new technologies become available; and
- how rapidly companies and households respond to price changes.

In a trivial sense, any annual rate of emissions reduction is possible if policy-makers are prepared to countenance big enough falls in output and employment. But analyses of this problem generally assume that such falls are unacceptable – an assumption borne out by the reaction to the recent global economic slowdown. The problem is to assess the speed of emissions reduction that is likely to be feasible while still attempting to achieve full employment of resources.

[8] These values are based on the baseline (lower aerosol) scenario.

Bowen and Ranger (2009) reviewed the evidence from economic modelling about the feasibility and costs of the reductions necessary to have a 50 per cent chance of avoiding an increase in global average temperature of more than 2°C above its pre-industrial level. Some models suggest that a 2°C goal is infeasible, let alone a 1.5°C goal. For example, in the most recent Stanford Energy Modeling Forum exercise, six out of 14 models were unable to produce a scenario with long-run stabilisation at 450 parts per million of carbon-dioxide-equivalent, even with full and immediate participation by all countries and some limited overshoot of the stabilisation target permitted (Clarke *et al.*, 2009). Other models are more optimistic, as illustrated by the work of the ADAM, AVOID and RECIPE projects (Knopf *et al.*, 2009; Bosetti *et al.*, 2010; Edenhofer *et al.*, 2009).

But there is broad agreement that, as the temperature goal is lowered, achieving it becomes more and more difficult and expensive (assuming that capacity utilisation and unemployment rates do not change). That can be seen in the various scenarios considered by the WITCH modelling team in their work for the AVOID project. As Figure 3 shows, as the goal is lowered towards 2°C, the costs (measured in terms of the net present value of GDP losses) mount at an accelerating rate; the 1.5°C goal is infeasible given the WITCH model's parameterisation. The question arises: are the extra benefits from aiming for 1.5°C instead of 2°C worth the increase in global costs and the risk that the goal may be unattainable?

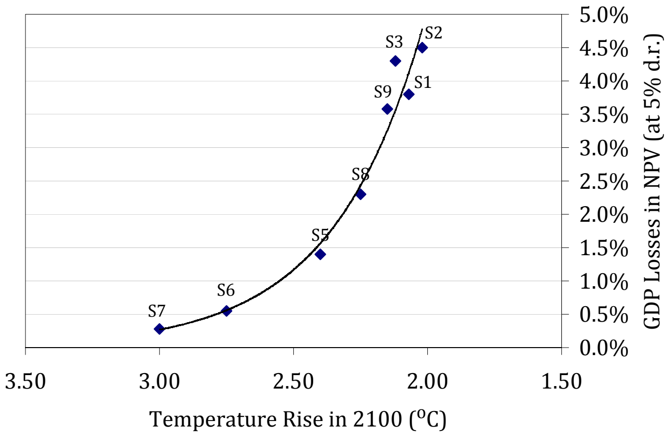

Figure 3: The relationship between temperature goal and GDP costs using the WITCH model. Source: Bosetti et al. (2010)

Another way to consider the feasibility of the 1.5°C goal is to ask whether the annual rates of emissions reduction implied are plausible. den Elzen *et al*. (2007) analysed 40 SRES no-climate-policy scenarios and 18 post-SRES mitigation scenarios to identify the maximum annual rate of emissions reduction. They found that, with only a few exceptions, the maximum rate was less than 3 per cent, and chose to impose 3 per cent as a 'speed limit' restriction on the pace of reductions in their own modelling exercise. Yet we calculate that an annual reduction rate of at least 3 per cent is needed after 2020. Other studies that have not imposed arbitrary 'speed limits' have suggested that higher rates of around 6 per cent are possible for a while in certain circumstances, but only when the conditions have been put in place for rapid investment in decarbonisation of the energy sector (e.g. Knopf *et al.*, 2009; Edenhofer *et al.*, 2009).

To illustrate that such rates of change are historically unprecedented, consider the rate of decarbonisation of GDP that would be necessary if the world grows in line with the projections of the International Energy Agency in its 2009 World Energy Outlook (the WEO reference scenario is similar to that used in this study). The WEO envisages average annual world GDP growth of 3 per cent from 2015 to 2030. If emissions are to drop at an average annual rate of 3 per cent, that requires the greenhouse-gas-intensity of GDP to fall by 5.8 per cent per year on average. If emissions are to drop at a rate of 6 per cent, the greenhouse-gas-intensity of GDP has to fall by 8.7 per cent per year on average. As Figure 4 shows, focusing on carbon intensity of GDP, there is very little precedent for such rates among the countries that were the top 25 emitters in 1990 (the Figure shows the distribution of average annual rates of reduction of carbon intensity over the periods 1990-95, 1995-2000 and 2000-05). Such rates, however, are feasible. And one must remember that strong climate change policies were not in place anywhere between 1990 and 2005.

Overall, a significant risk remains that the 1.5°C goal is infeasible, even with immediate and comprehensive application of well-designed policies. If it is feasible, it is likely to entail considerably higher global costs than the 2°C goal, which would be reflected in higher global energy costs and lower world consumption than would otherwise be the case

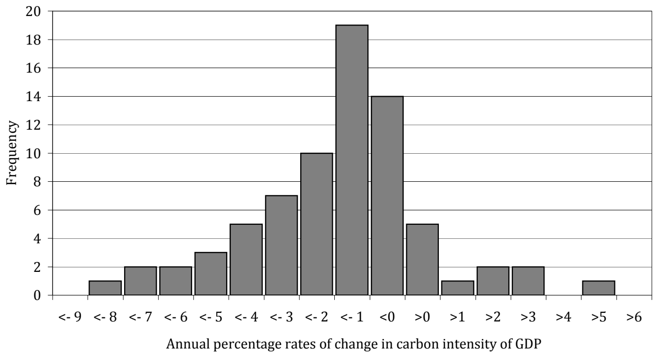

Figure 4: Annual percentage rates of change in carbon intensity of GDP over 1990-95, 1995-2000 and 2000-05 for the top 25 emitting nations in 1990. Source: WRI CAIT (2010).

Low annual global emissions by 2100 and a floor of zero emissions in the long term

The feasibility of a floor of zero emissions remains a matter for debate (e.g. Ranger *et al.*, 2009). In practice, a floor of zero emissions would be likely to require widespread use of various forms of carbon capture and storage (e.g. for biomass burning), chemical sequestration of carbon, and various other geo-engineering solutions. These technologies would have ‘negative net emissions’ and could offset residual emissions in sectors such as agriculture where emissions reductions would be particularly difficult. But it is not clear whether such technologies are feasible on the scale needed, nor whether they will be safe and reliable over long time horizons.

An assumption that it is possible return to a temperature goal of 1.5°C over many decades after overshooting.

The scenarios explored in this study assume that global average temperature could peak and then fall if emissions are reduced to a given level. The science involved in simulating such scenarios (in particular, the detailed interactions of the carbon cycle) is not well understood (e.g. Lowe *et al.*, 2009). In particular, there is currently a scientific debate about how quickly atmospheric concentrations of greenhouse gases would decline following large reductions in emissions from human activities. This is particularly the case for atmospheric carbon dioxide, because some earth system models show very slow rates of decline (e.g. Matthews and Weaver, 2010). However, several models do show that atmospheric concentrations of greenhouse gases would decline if there were rapid reductions in emissions from human activities (e.g. Plattner *et al.*, 2008). For shorter-lived greenhouse gases, such as methane, a decline in atmospheric concentrations following rapid reductions in emissions is less uncertain.

There is also some uncertainty about how quickly global average temperature would respond to reductions in atmospheric concentrations and climate forcing. To some extent this is likely to depend on the size of the top-of-atmosphere imbalance when emission reductions begin, and the rate of reduction in greenhouse gas concentrations that would occur. This means that there is a risk that global temperature would not reduce as quickly as the model used in this study suggests. There is also evidence that some important systems, such as the hydrological cycle, may be much slower to recover than global average temperature (Wu *et al.*, 2010).

The higher peak temperature associated with overshooting a temperature goal would generate greater risks of triggering large-scale and potentially irreversible impacts, such as a loss of some species, inundation of land areas and extensive bleaching of coral reefs (Fischlin *et al.*, 2007). A robust finding from research is that higher sustained warming levels are more likely to trigger accelerated or irreversible changes in the climate system. Some of these potentially dangerous large-scale system changes, such as enhanced release of carbon from currently frozen soils or accelerated loss of the Amazon forest, would make it more difficult to return to lower temperatures on a timescale of decades. However, much less evidence is available about whether the Amazon forest, high latitude frozen soils or ice sheets could temporarily cope with a higher global average temperature without becoming committed to large long-term changes. Thus, given the current state of scientific understanding, overshoot scenarios must be considered with caution. More research is needed into the likelihood of triggering feedbacks or irreversible impacts, such as large rises in sea level, during temporary overshooting of a 1.5°C goal.

Conclusions

Our findings suggest that even with early and strong action to reduce emissions, the likelihood of avoiding global warming of more than 1.5°C above the pre-industrial level is low. However, it may be possible to limit the rise to no more than 1.5°C above the pre-industrial level in the long term, if global average temperature is allowed to overshoot the goal and fall over a period of several decades.

However, there are large uncertainties about the science of overshooting a temperature goal, and such scenarios require a number of assumptions to be feasible. In the modelling framework we have used in this study, we have found that early and strong reductions in annual global emissions would be required, beginning within the next five years (i.e. no later than 2015), and resulting in a fall to no more than about 48 billion tonnes of carbon-dioxide-equivalent by 2020. We have also found that rapid rates of annual reductions in emissions, possibly as high as 4 or 5 per cent per year, would be required after 2020. In addition, annual global emissions would need to decline to a small fraction of 1990 levels by 2100, and to continue to reduce to nearly zero over the long term. We have also noted that the modelling of emissions paths involves large uncertainties, which mean that the feasibility of achieving a 1.5°C goal is far from clear, and it is likely to be much more difficult to achieve than a 2°C goal. Attempting to do so would be likely to incur substantial extra costs relative to GDP.

Given the current uncertainties, one approach for policy-makers may be to take actions that will allow the option of switching at some later point to an emissions path that is consistent with a 1.5°C goal. Our analysis suggests that the range of global annual emissions of 40 to 48 billion tonnes of carbon-dioxide-equivalent in 2020 (which was identified by Ranger *et al*. (2009) as consistent with a 2°C goal) might also be compatible with a 1.5°C goal, if it is assumed that emissions reductions could be quickly accelerated after 2020. Our findings suggest that aiming for the bottom end of this range for 2020 (i.e. taking strong action now) would reduce the risk of closing down the option of switching to a 1.5°C goal. Conversely, aiming for the top end of the range in 2020 would reduce the chances of exercising that option, even if an overshoot of global average temperature was considered acceptable. To limit the overshoot to less than 50 years would require annual global emissions to fall at a rate of 5 per cent per year or more, the feasibility of which is unclear. We note that these paths offer a 50 per cent chance of limiting global average temperature to no more than 1.5°C above its pre-industrial in the long term, based on the current understanding. To have a much higher probability of avoiding such warming would require far greater and faster action to reduce global annual emissions of greenhouse gases.

We hope that this study will help to inform negotiations between Parties to the UNFCCC, including discussions about emissions reductions targets for 2020. It should be noted that the pledges listed in the Appendices to the Copenhagen Accord relate almost exclusively to targets for 2020, and so have limited use in helping to determine likely future changes in global average temperature, as they provide no information about actions beyond 2020. Some researchers have attempted to estimate a future temperature, based on the intended actions listed in the Copenhagen Accord, by making assumptions, in the absence of explicit statements, about countries' intentions. Such analyses inevitably conclude that even a 2°C goal could not be achieved (e.g. Rogelj *et al.*, 2010) solely because of pessimistic assumptions about the path of global annual emissions after 2020. In our view, the value of such speculative analyses is unclear if they involve unduly pessimistic assumptions, such as developing countries largely failing to limit their emissions after 2020 - more optimistic assumptions about post-2020 emissions would lead to much more positive assessments of the prospects for achieving a 2°C goal.

Acknowledgements

Laila Gohar and Jason Lowe were supported during this project by the AVOID programme. Sarah Raper provided useful guidance on model set up and performance. The Met Office Hadley Centre provided scientific input to this work but does not advocate particular policy choices. We thank Brian Hoskins, Andrew Gouldson, Piers Forster and Nicholas Stern for helpful comments about earlier drafts of this document, and James Rydge for the analysis of historical rates of change in carbon intensity of GDP.

References

Bosetti, V., Carraro, C. and Tavoni, M. 2010. Report on costs of different paths towards a low carbon world. AVOID report AV/WS2/D1/04. Met Office, Exeter, UK.

Bowen, A. and Ranger, N. 2009a. *Mitigating climate change through reductions in greenhouse gas emissions: the science and economics of future paths for global annual emissions.* Policy brief, December. Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London, UK. 43pp. http://www2.lse.ac.uk/GranthamInstitute/publications/PolicyBriefsandPapers/PBMitigatingBowenRangerDec09.pdf.

Bowen, A. and Ranger N. 2009b. Mitigating climate change with reductions in greenhouse gas emissions: economic assessment of emissions targets. In: Bowen, A. and Ranger, N., *Mitigating climate change through reductions in greenhouse gas emissions: the science and economics of future paths for global annual emissions.* Policy brief, December. Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London, UK. p.21-34. http://www2.lse.ac.uk/GranthamInstitute/publications/PolicyBriefsandPapers/PBMitigatingBowenRangerDec09.pdf.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S. and Tavoni, M. 2009. International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics*, v.31, Special Supplement 2, p.S64-S81.

den Elzen, M., Meinshausen, M. and van Vuuren, D. 2007. Multi-gas envelopes to meet greenhouse gas concentration targets: costs versus certainty of limiting temperature increase. *Global Environmental Change*, v.17, p.260-280.

Edenhofer, O., Carraro, C., Hourcade, J.-C., Neuhoff, K., Luderer, G., Flachsland, C., Jakob, M., Popp, A., Steckel, J., Strohschein, J., Bauer, N., Brunner, S., Leimbach, M., Lotze-Campen, H., Bosetti, V., de Cian, E., Tavoni, M., Sassi, O., Waisman, H., Crassous-Doerfler, R., Monjon, S., Dröge, S., van Essen, H., del Río, P., and Türk A. 2009. *The Economics of Decarbonization. Report of the RECIPE project*. Potsdam Institute for Climate Impact Research, Potsdam.

Fischlin, A., Midgley G.F., Price J.T., Leemans R., Gopal B., Turley C., Rounsevell M.D.A., Dube, J. Tarazona O.P. and Velichko A.A. 2007. Ecosystems, their properties, goods, and services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* (M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, eds.), Cambridge University Press, Cambridge, p.211-272.

Gohar, L.K. and Lowe, J.A. 2010. Summary of the emissions mitigation scenarios. AVOID report AV/WS1/D1/02. Met Office. UK.

International Energy Agency 2009. *World Energy Outlook 2009*. http://www.worldenergyoutlook.org/2009.asp.

Knopf, B., and Edenhofer, O., with Barker, T., Bauer, N., Baumstark, L., Chateau, B., Criqui, P., Held, A., Isaac, M., Jakob, M., Jochem, E., Kitous, A., Kypreos, S., Leimbach, M., Magné, B., Mima, S., Schade, W., Scrieciu, S., Turton, H. and van Vuuren, D. 2009. The economics of low stabilisation: implications for technological change and policy. To appear as Chapter 11 in Making climate change work for us - ADAM synthesis book (M. Hulme and H. Neufeldt, eds), Cambridge University Press, UK.

Lowe, J.A., Gohar, L.K., Huntingford, C., Good, P., Bernie, D., Pardaens, A., Warren, R. and Raper, S.C.B. 2010. Are the emission pledges in the Copenhagen Accord compatible with a global aspiration to avoid more than 2°C of global warming? A Technical Note from the AVOID Programme. http://www.avoid.uk.net/

Lowe, J.A., Huntingford, C., Raper, S.C.B., Jones, C.D., Liddicoat, S.K. and Gohar, L.K. 2009: How difficult is it to recover from dangerous levels of global warming? *Environmental Research Letters*, v.4, 014019, p.9.

Matthews H.D. and Weaver A.J. 2010. Committed climate warming. *Nature Geoscience*, v.3, p.142-143.

McKinsey & Company 2009. *Pathways to a low-carbon economy.*

Plattner, G.K., Knutti R., Joos F., Stocker, T. F., von Bloh, W., Brovkin, V., Cameron, D., Driesschaert, E., Dutkiewicz, S., Eby, M., Edwards, N. R., Fichefet, T., Hargreaves, J. C., Jones, C. D., Loutre, M. F., Matthews, H. D., Mouchet, A., Mueller, S. A., Nawrath, S., Price, A. R., Sokolov, A., Strassmann, K. M. and Weaver, A. J. 2008. Long-term climate commitments projected with climate-carbon cycle models, *Journal of Climate,* v.21, p. 2721-2751.

Ranger, N., Bowen, A., Lowe, J. and Gohar, L. 2009. Mitigating climate change through reductions in greenhouse gas emissions: climate science constraints on annual global emissions targets for 2020 and 2050. In: Bowen, A. and Ranger, N., *Mitigating climate change through reductions in greenhouse gas emissions: the science and economics of future paths for global annual emissions.* Policy brief, December. Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London, UK. p.14-20. http://www2.lse.ac.uk/GranthamInstitute/publications/PolicyBriefsandPapers/PBMitigatingBowenRangerDec09.pdf.

Rogelj, J., Nabel, J., ,Chen,, C., Hare, W., Markmann, K., Meinshausen, M., Schaeffer, M., Macey, K. and Höhne, N. 2010. Copenhagen Accord pledges are paltry. Opinion. *Nature*, v.464, p.1126-1128.

Stern, N. 2009. *Deciding our future in Copenhagen: will the world rise to the challenge of climate change?* Policy brief, December. Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London, UK. 17pp. http://www2.lse.ac.uk/GranthamInstitute/publications/PolicyBriefsandPapers/PBActionSternDec09.pdf

Stern, N. and Taylor, C. 2010. *What do the Appendices to the Copenhagen Accord tell us about global greenhouse gas emissions and the prospects for avoiding a rise in global average temperature of more than 2°C?* Policy paper, March. Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London, UK. 26pp. http://www2.lse.ac.uk/GranthamInstitute/publications/PolicyBriefsandPapers/PPCOPAccordSternTaylorMarch10.pdf

United Nations Framework Convention on Climate Change 2010a. *Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009. Addendum. Part Two: Action taken by the Conference of the Parties at its fifteenth session.* Bonn, Germany. 43pp. http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf

United Nations Framework Convention on Climate Change 2010b. *Text to facilitate negotiations among Parties. Note by the Chair.* Ad Hoc Working Group on Long-term Cooperative Action under the Convention. 9 July. Bonn, Germany. 45pp. http://unfccc.int/resource/docs/2010/awglca11/eng/08.pdf

Wigley, T.M.L. and. Raper, S.C.B. 2001. Interpretation of high projections for global-mean warming. *Science*, v.293, p.451–454.

Wu, P., Wood, R., Ridley, J. and Lowe, J. 2010. Temporary acceleration of the hydrological cycle in response to a CO2 rampdown. *Geophysical Research Letters*, v.137, L12705.

Grantham Research Institute on Climate Change and the Environment

Centre for Climate Change Economics and Policy

Met Office Hadley Centre

The Grantham Foundation for the Protection of the Environment

E·S·R·C Economic & Social Research Council

LSE The London School of Economics and Political Science

University of Leeds