Implications of potentially lower climate sensitivity on climate projections and policy

Perspective

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Joeri Rogelj[1,2],
Malte Meinshausen[3,4],
Jan Sedláček[1] **and**
Reto Knutti[1]

[1] *Institute for Atmospheric and Climate Science, ETH Zurich, Universitätstrasse 16, 8092 Zürich, Switzerland*
[2] *Energy Program (ENE), International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria*
[3] *Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, D-14412, Potsdam, Germany*
[4] *School of Earth Sciences, The University of Melbourne, 3010 Melbourne, Victoria, Australia*
E-mail:
joeri.rogelj@env.ethz.ch

Abstract

Climate sensitivity, the long-term temperature response to CO_2, has been notoriously difficult to constrain until today. Estimates based on the observed warming trends favor lower values, while the skill with which comprehensive climate models are able to simulate present day climate implies higher values to be more plausible. We find that much lower values would postpone crossing the 2 °C temperature threshold by about a decade for emissions near current levels, or alternatively would imply that limiting warming to below 1.5 °C would require about the same emission reductions as are now assumed for 2 °C. It is just as plausible, however, for climate sensitivity to be at the upper end of the consensus range. To stabilize global-mean temperature at levels of 2 °C or lower, strong reductions of greenhouse gas emissions in order to stay within the allowed carbon budget seem therefore unavoidable over the 21st century. Early reductions and the required phase-out of unabated fossil fuel emissions would be an important societal challenge. However, erring on the side of caution reduces the risk that future generations will face either the need for even larger emission reductions or very high climate change impacts.

1. Introduction

Equilibrium climate sensitivity (ECS), the equilibrium global-mean surface temperature change for a doubling of the atmospheric CO_2 concentration, is a key characteristic of the climate system. Despite large efforts, recent estimates for ECS from various methods are diverging, and much has been speculated over the implications of some low estimates. Energy-balance models that take into account the reduced rate of surface warming in the last decade (also referred to in the literature as 'hiatus', see Box TS.3 in IPCC 2013) present lower estimates, while the state-of-the-art atmosphere–ocean general circulation models (AOGCM) confirm earlier estimates and even suggest that the higher end could be more likely. Past assessments and reviews indicated that ECS is likely (>66%) in the range of 2–4.5 °C, very likely (>90%) larger than 1.5 °C, with a most likely value around 3 °C (IPCC 2007, Knutti and Hegerl 2008). Some newer studies have confirmed that range (Andrews *et al* 2012, Rohling *et al* 2012), but others have raised the possibility that ECS may be either lower (Schmittner *et al* 2011, Aldrin *et al* 2012, Lewis 2013, Otto *et al* 2013) or higher (Fasullo and Trenberth 2012, Sherwood *et al* 2014) than previously thought. The current assessment of the Intergovernmental Panel on Climate Change (IPCC 2013), states that ECS is likely (>66%) in the range of 1.5–4.5 °C, extremely likely (>95%) larger than 1 °C, and very unlikely (<10%) larger than 6 °C. No most likely value is provided.

The question thus arises how important this uncertainty in ECS is for climate policy. How do these diverging estimates influence the emission reduction requirements to limit warming to below particular temperature thresholds, like 1.5 °C or 2 °C? To inform policy-makers we here assess and discuss policy

implications of changing ECS estimates. We do not attempt to put a definitive number on ECS, but simply explore the consequences of different ECS distributions for climate change mitigation.

2. Methodology

We selected a set of ECS distributions, each of which is consistent with a recent ECS estimate or combinations of those. Four cases are highlighted in this analysis: those based on the consensus estimates from the IPCC Fourth and Fifth Assessment Reports (AR4 and AR5, respectively), a low estimate based on the observed recent warming and ocean heat uptake (Aldrin *et al* 2012), and a high estimate based on how well climate models represent the current climate (a full set of 10 cases are shown in tables S1, S2, and figure S1 available at stacks.iop.org/ERL/9/031003/mmedia). Although this selection is illustrative, it spans a wide range of plausible estimates. We then use the methodology of Meinshausen *et al* (2009) to constrain an energy-balance carbon-cycle climate model (Meinshausen *et al* 2011a, 2011b) to historical forcing estimates, and observations of hemispheric temperatures and ocean heat uptake, while sampling the parameter space in a way such that the posterior distribution of ECS reflects the different possible distributions. With this setup we can produce for each ECS distribution a range of temperature outcomes that is consistent with the underlying uncertainty in ECS distribution (Rogelj *et al* 2012).

3. Results

A first interesting question is to determine by how much temperature projections for the year 2100 would vary depending on which ECS distribution is assumed. We look at this by means of a set of four scenarios, which range from a very high greenhouse gas emission future in absence of any climate change mitigation to a very stringent mitigation scenario (the representative concentration pathways, RCPs). The variation in the median temperature outcome by 2100 is similar across scenarios: -24 to $+17\%$ and -22 to $+13\%$ in the lowest and highest scenario, respectively (figure 1, pink and green range relative to the black range, and figure S2 available at stacks.iop.org/ERL/9/031003/mmedia). In absolute terms, however, this means that, depending on the ECS distribution one applies, median temperature outcomes by the end of the century can shift by about -1.0 to $+0.6\,°C$ and -0.4 to $+0.3\,°C$ in the highest and lowest RCP scenario, respectively. When assuming an ECS distribution that is consistent with the IPCC AR5 ECS assessment instead of the AR4 assessment, no significant shift of temperatures can be seen, indicating the high coherence of the IPCC ECS estimates across these assessments.

The temperature changes are smaller than what a simple look at the absolute shifts in the estimates of ECS would suggest. The reason for this is that the ratio of warming to forcing is approximately equal to what is called the transient climate response (Frame *et al* 2006, Meehl *et al* 2007, Gregory and Forster 2008, Knutti *et al* 2008). The transient climate response (TCR) is defined as the global-mean surface temperature change at the time of CO_2 doubling following a linear increase in CO_2 forcing over a period of 70 years. It thus characterizes the warming at a given time following a steady increase in forcing over several decades. However, ECS and TCR are not unrelated. TCR-defined warming is not yet in equilibrium and, if concentrations are kept constant, temperatures will slowly evolve to a level consistent with the ECS. Important information for climate policy is that TCR is lower than ECS, and the relationship is nonlinear, with TCR becoming insensitive to ECS for high values of ECS (Knutti *et al* 2005,
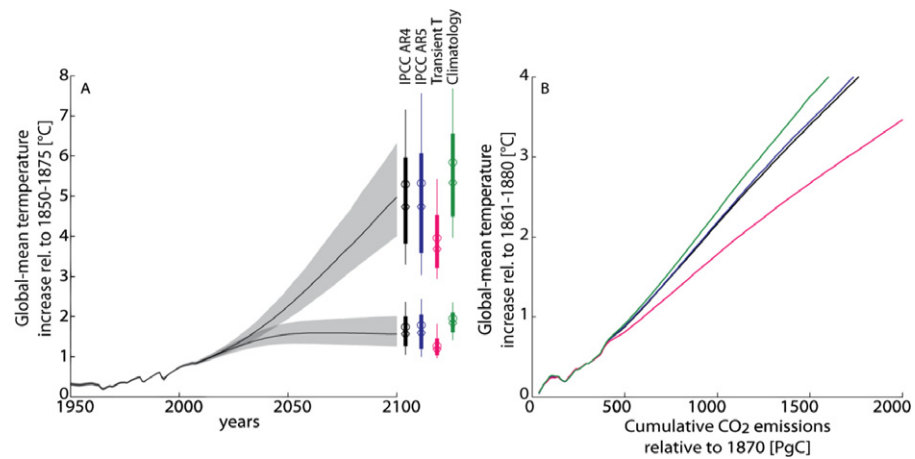
Figure 1. Panel A—Temperature projections for the RCP3-PD (lowest scenario) and RCP8.5 (highest scenario) over the 21st century assuming an ECS distribution consistent with the IPCC AR4 statement (grey areas show 66% ranges, thin lines within these ranges show the median), with temperature projections for RCP3-PD and RCP8.5 for 2091–2100, consistent with the four illustrative ECS distributions highlighted in this study. Thin (thick) lines indicate the 90% (66%) range. Diamonds and circles show the median and average, respectively. Panel B—Relationship between cumulative CO_2 emissions and global-mean temperature increase (66th percentile) as computed by our model for our four illustrative ECS distributions. See figures S2 and S3 (available at stacks.iop.org/ERL/9/031003/mmedia) for other RCPs and additional information.

Allen *et al* 2006). For projections of warming until the end of this century, TCR is arguably of higher relevance than ECS alone. This implies that while there is a lot of variation over the set of ECS estimates that we consider in this study, TCR estimates consistent with each of these ECS estimates differ much less (see figure S1 available at stacks.iop.org/ERL/9/031003/mmedia).

The expected warming from a given evolution in greenhouse gas emissions over the coming century is thus better constrained than the spread in ECS estimates would suggest. This does not mean that possible variations are negligible. A scenario that under the current ECS estimates of the IPCC would lead to a 81% chance of keeping global-mean temperature increase below the widely discussed 2 °C limit in our framework, would end up with a lower (72%) chance of doing so if current suggestions that ECS is at the high end of the range turn out to be correct. Alternatively, if ECS and TCR end up at the very low end of the current literature range, the chances to stay below 2 °C would increase to 98% with this scenario (see highlighted cases in table S3 available at stacks.iop.org/ERL/9/031003/mmedia).

Another policy-relevant question is how carbon budgets, compatible with limiting warming to below particular temperature thresholds, are affected by ECS uncertainty. Carbon budgets, i.e., the amount of CO_2 that can be emitted for temperature to remain below a chosen threshold with a given likelihood (Meinshausen *et al* 2009, Allen *et al* 2009), provide key information, in particular when combined with feasible emissions corridors (see figure 2, panel A) that take into account technological and economic constraints to keep yearly emissions over time within these budgets (Rogelj *et al* 2011). Also here the variation of carbon budgets is smaller than the variation of ECS estimates. For example, median ECS estimates of the four cases that we highlight are up to 25% higher or 45% lower than our ECS interpretation of the IPCC AR5 assessment. However, for limiting warming to below 2 °C, changes in the levels of compatible cumulative emissions are smaller. We find a variation of −10 to +15% around our IPCC-AR5-based estimate, depending on ECS case and probability level (figures 1 and S3 available at stacks.iop.org/ERL/9/031003/mmedia).
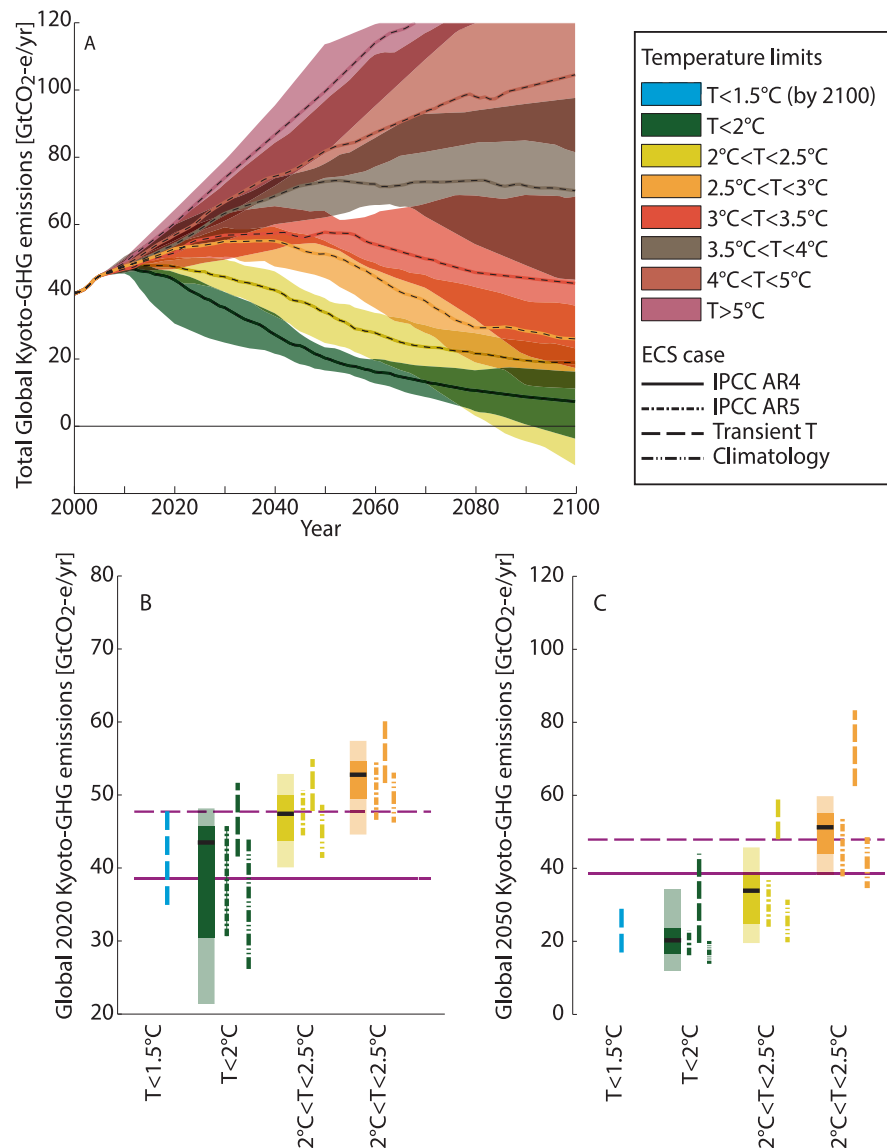
Figure 2. Emission corridors consistent with limiting warming to various temperature levels with at least 66% chance, based on the methodology and scenarios described in Rogelj *et al* (2011) for our ECS case consistent with the IPCC AR4 (panel A). Dashed lines show the median path, ranges the 15th–85th percentile range. Panels B and C show time slices of consistent emissions in the year 2020 and 2050, respectively, for pathways consistent with limiting warming below 2 (green), 2.5 (yellow) and 3 °C (orange) relative to pre-industrial during the 21st century with at least 66% chance. Light blue dashed lines in panels B, and C show results for emission pathways that keep warming to below 1.5 °C by the end of the century with at least 66% chance. These values are only available for our lowest ECS case based on the transient temperature evolution, because for the other ECS cases only too few scenarios are available in our scenarios set for this category. Light shaded areas in panels B and C represent the minimum–maximum ranges; the dark shaded areas represent the 15th–85th percentile range, and the thick black horizontal lines the median values for our ECS case consistent with the IPCC AR4 as shown in panel A. Vertical lines in panels B and C show the 15th–85th percentile range for three ECS variations. Horizontal solid and dashed purple lines the median 1990 and 2010 emission levels, respectively, in our modeling framework.

Finally, looking at emission corridors compatible with temperature limits, moving from previous to current ECS estimates of the IPCC does not make a big difference (figure 2, panels B and C). However, when applying more extreme estimates, emission ranges consistent with two 2 °C can shift markedly (for example, by +40 and −15% in 2050 for the medians). Interestingly, under the assumption of our lowest ECS case (reflecting studies inferring ECS from

observed transient temperatures), emission levels until 2050 consistent with limiting warming to below 1.5 °C by 2100 with more than 66% chance become very similar to the emission levels consistent with 2 °C assuming the IPCC assessment's distribution for ECS (figures 2 and S4 available at stacks.iop.org/ERL/9/031003/mmedia). On the other hand, for our highest ECS case (inferred from AOGCMs and observed climatology) emission pathways consistent with 2 °C remain broadly similar with the results based on the IPCC assessments, but for higher temperature limits (like 2.5 or 3 °C) the shift towards lower emissions is much more pronounced (see figure S4 available at stacks.iop.org/ERL/9/031003/mmedia).

4. Discussion and conclusion

There are several climate policy implications that can be drawn from recent ECS estimates. The most important, however, is that they do not change the big picture if all available evidence is taken into account.

An important point is that there are currently multiple lines of evidence for supporting different ECS estimates, which point in various directions. A critical look at the various lines of evidence shows that those pointing to the lower end are sensitive to the particular realization of natural climate variability (Huber *et al* 2014). As a consequence, their results are strongly influenced by the low increase in observed warming during the past decade (about 0.05 °C/decade in the 1998–2012 period compared to about 0.12 °C/decade from 1951 to 2012, see IPCC 2013), and therewith possibly also by the incomplete coverage of global temperature observations (Cowtan and Way 2013). Studies that point towards the lower end also rely on simple energy-balance models with constant feedbacks for all forcings—and forcing quantifications that are derived from various modeling exercises. On the other hand, the studies that point towards the higher end (Fasullo and Trenberth 2012, Sherwood *et al* 2014) use different methods and draw upon insights from state-of-the-art general circulation models. They use the skill of such general circulation models in terms of how well they represent key climatological features, in particular those which are of importance for the temperature response of the climate to an increase in forcing. It is important to note that all methods are therefore a combination of models and observations, each with its own limitations, and none is clearly superior at this point.

Drawing upon the combined information of these multiple lines of evidence shows that there is no scientific support to diminish the urgency of emission reductions if warming is to be kept below 1.5 or 2 °C, the two temperature limits currently being discussed within the United Nations (UNFCCC 2010). Even the lowest ECS estimate assumed in this study only results in a delay of less than a decade in the timing of when the 2 °C threshold would be crossed when emission trends from the past 10 years are continued. Alternatively, if significantly lower ECS estimates were to be confirmed, following a low emissions trajectory (consistent with RCP3-PD) would become consistent with limiting warming below 1.5 °C by the end of the century with high probability (>80%) instead of only low probabilities (around 40%), and limiting warming to 1.5 °C would require about the same emission reductions as are now consistent with 2 °C when assuming the current IPCC ECS assessment.

Relatively small shifts of ECS distributions towards lower values have a small influence on the temperature outcome and on compatible emissions, when compared to the overall uncertainty. As international climate policy is concerned about limiting warming below 2 °C with a 'likely' chance (UNFCCC 2011) ('likely' denoting and 'at least 66% probability' (Mastrandrea *et al* 2010)), shifts that robustly constrain the high end of the ECS or TCR distributions would be most important.

With this study we show that betting on the optimistic message of a few recent studies is risky at this point for two important reasons. First, as pointed out above, recent low ECS estimates are only part of the story. Alternative, and equally convincing methods point to higher values of ECS and only looking at the lower estimates would thus obfuscate an important part of the available scientific evidence. Second, not taking into account the combined evidence and delaying emission reductions in the coming decades would lead to lock-in into energy- and carbon-intensive infrastructure. This would thus not only result in a lower remaining carbon budget for the rest of the century, but the world would also be on a much more costly path by 2030 (Rogelj *et al* 2013b, 2013a, Luderer *et al* 2013, Riahi *et al* 2013). If current policies would bet on the optimistic end of the range, and more pessimistic estimates turn out to better capture the Earth system's behavior, limiting warming to low levels (like 2 °C) might well become unattainable (Rogelj *et al* 2013a, 2013b, Luderer *et al* 2013).

In conclusion, in light of the large uncertainties that still exist, the lack of consensus across different studies and lines of evidence, and the weak constraint that the observations provide, we argue that the possibility of lower values for ECS and TCR does not reduce the urgency for climate mitigation. On the contrary, a risk-averse strategy points to more ambitious reductions compared to what countries presented so far (Rogelj *et al* 2013a, UNEP 2013, Riahi *et al* 2013). Hedging against this uncertainty can be done by reducing global carbon emissions without delay, as to limit cumulative carbon emissions to within a budget in line with medium and higher climate response estimates that currently cannot be excluded. For our current generation, early and deep reductions of carbon emissions will undoubtedly be an important global societal challenge, despite the multiple opportunities and benefits that they bring along, such as reduced air pollution, energy security etc (McCollum *et al* 2013). However, those challenges are likely small compared to what future generations otherwise might possibly face: high climate impacts or emission reduction rates and associated costs that are substantially higher than the ones that would be necessary, if mitigation action commenced today.

References

Aldrin M, Holden M, Guttorp P, Skeie R B, Myhre G and Berntsen T K 2012 Bayesian estimation of climate sensitivity based on a simple climate model fitted to observations of hemispheric temperatures and global ocean heat content *Environmetrics* **23** 253–71

Allen M R *et al* 2006 *Avoiding Dangerous Climate Change* ed H J Schellnhuber *et al* (Cambridge: Cambridge University Press)

Allen M R, Frame D J, Huntingford C, Jones C D, Lowe J A, Meinshausen M and Meinshausen N 2009 Warming caused by cumulative carbon emissions towards the trillionth tonne *Nature* **458** 1163–6

Andrews T, Gregory J M, Webb M J and Taylor K E 2012 Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere–ocean climate models *Geophys. Res. Lett.* **39** L09712

Cowtan K and Way R G 2013 Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends *Q. J. R. Meteorol. Soc.*

Fasullo J T and Trenberth K E 2012 A less cloudy future: the role of subtropical subsidence in climate sensitivity *Science* **338** 792–4

Frame D J, Stone D A, Stott P A and Allen M R 2006 Alternatives to stabilization scenarios *Geophys. Res. Lett.* **33** L14707

Gregory J M and Forster P M 2008 Transient climate response estimated from radiative forcing and observed temperature change *J. Geophys. Res.* **113** D23105

Huber M, Beyerle U and Knutti R 2014 Estimating climate sensitivity and future temperature in the presence of natural climate variability *Geophys. Res. Lett.* 2013GL058532

IPCC 2007 *Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report* (Cambridge: Cambridge University Press) p 994

IPCC 2013 *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Intergovernmental Panel on Climate Change Fifth Assessment Report* (Cambridge: Cambridge University Press)

Knutti R *et al* 2008 A review of uncertainties in global temperature projections over the twenty-first century *J. Clim.* **21** 2651–63

Knutti R and Hegerl G C 2008 The equilibrium sensitivity of the Earth's temperature to radiation changes *Nature Geosci.* **1** 735

Knutti R, Joos F, Müller S A, Plattner G-K and Stocker T F 2005 Probabilistic climate change projections for CO_2 stabilization profiles *Geophys. Res. Lett.* **32** L20707

Lewis N 2013 An objective Bayesian, improved approach for applying optimal fingerprint techniques to estimate climate sensitivity *J. Clim.* **26** 7414–29

Luderer G, Pietzcker R C, Bertram C, Kriegler E, Meinshausen M and Edenhofer O 2013 Economic mitigation challenges: how further delay closes the door for achieving climate targets *Environ. Res. Lett.* **8** 034033

Mastrandrea M D *et al* 2010 *Guidance Notes for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties* IPCC, p 5 available at www.ipcc.ch

McCollum D, Krey V, Riahi K, Kolp P, Grubler A, Makowski M and Nakicenovic N 2013 Climate policies can help resolve energy security and air pollution challenges *Clim. Change* 1–16 doi:10.1007/s10584-013-0710-y (in press)

Meehl G A *et al* 2007 *IPCC Fourth Assessment Report* ed S Solomon *et al* (Cambridge: Cambridge University Press)

Meinshausen M, Meinshausen N, Hare W, Raper S C B, Frieler K, Knutti R, Frame D J and Allen M R 2009 Greenhouse-gas emission targets for limiting global warming to 2 °C *Nature* **458** 1158–62

Meinshausen M, Raper S C B and Wigley T M L 2011a Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—part 1: model description and calibration *Atmos. Chem. Phys.* **11** 1417–56

Meinshausen M, Wigley T M L and Raper S C B 2011b Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—part 2: applications *Atmos. Chem. Phys.* **11** 1457–71

Otto A *et al* 2013 Energy budget constraints on climate response *Nature Geosci.* **6** 415–6

Riahi K *et al* 2013 Locked into Copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals *Technol. Forecast. Soc. Change* at press

Rogelj J, Hare W, Lowe J, van Vuuren D P, Riahi K, Matthews B, Hanaoka T, Jiang K and Meinshausen M 2011 Emission pathways consistent with a 2 °C global temperature limit *Nature Clim. Change* **1** 413–8

Rogelj J, McCollum D L, O'Neill B C and Riahi K 2013a 2020 emissions levels required to limit warming to below 2 °C *Nature Clim. Change* **3** 405–12

Rogelj J, McCollum D L, Reisinger A, Meinshausen M and Riahi K 2013b Probabilistic cost estimates for climate change mitigation *Nature* **493** 79–83

Rogelj J, Meinshausen M and Knutti R 2012 Global warming under old and new scenarios using IPCC climate sensitivity range estimates *Nature Clim. Change* **2** 248–53

Rohling E J *et al* 2012 Making sense of palaeoclimate sensitivity *Nature* **491** 683–91

Schmittner A, Urban N M, Shakun J D, Mahowald N M, Clark P U, Bartlein P J, Mix A C and Rosell-Melé A 2011 Climate sensitivity estimated from temperature reconstructions of the last glacial maximum *Science* **334** 1385–8

Sherwood S C, Bony S and Dufresne J-L 2014 Spread in model climate sensitivity traced to atmospheric convective mixing *Nature* **505** 37–42

UNEP 2013 *The Emissions Gap Report 2013—A UNEP Synthesis Report* (Nairobi, Kenya: UNEP) p 64

UNFCCC 2010 The Cancun agreements: outcome of the work of the ad hoc working group on long-term cooperative action under the convention FCCC/CP/2010/7/Add.1 Decision 1/CP.16 (Cancun: United Nations Framework) p 31

UNFCCC 2011 Establishment of an ad hoc working group on the Durban platform for enhanced action *Draft Decision -/CP.17* (Durban: United Nations Framework Convention on Climate Change) p 2