

LETTER

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The link between a global 2 °C warming threshold and emissions in years 2020, 2050 and beyond

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Abstract

In the Copenhagen Accord, nations agreed on the need to limit global warming to two degrees to avoid potentially dangerous climate change, while in policy circles negotiations have placed a particular emphasis on emissions in years 2020 and 2050. We investigate the link between the probability of global warming remaining below two degrees (above pre-industrial levels) right through to year 2500 and what this implies for emissions in years 2020 and 2050, and any long-term emissions floor. This is achieved by mapping out the consequences of alternative emissions trajectories, all in a probabilistic framework and with results placed in a simple-to-use set of graphics.

The options available for carbon dioxide-equivalent (CO₂e) emissions in years 2020 and 2050 are narrow if society wishes to stay, with a chance of more likely than not, below the 2 °C target. Since cumulative emissions of long-lived greenhouse gases, and particularly CO₂, are a key determinant of peak warming, the consequence of being near the top of emissions in the allowable range for 2020 is reduced flexibility in emissions in 2050 and higher required rates of societal decarbonization. Alternatively, higher 2020 emissions can be considered as reducing the probability of limiting warming to 2 °C. We find that the level of the long-term emissions floor has a strong influence on allowed 2020 and 2050 emissions for two degrees of global warming at a given probability. We place our analysis in the context of emissions pledges for year 2020 made at the end of and since the 2009 COP15 negotiations in Copenhagen.

Keywords: climate change, global warming, two degrees, carbon dioxide, greenhouse gases

 Online supplementary data available from stacks.iop.org/ERL/7/014039/mmedia

1. Introduction

Multiple scientific studies covering a broad range of potential impacts suggest unconstrained levels of global warming could have serious consequences. In the 2009 Copenhagen Accord, many nations agreed to ‘hold the increase in global temperature below 2 °C’ by initiating ‘deep cuts in global emissions’ (UNFCCC 2009). This was later ratified in the Cancun Agreements (UNFCCC 2010), including confirmation that the two degrees temperature increase is relative to the period just before industrial times.

Stabilization of global temperature will likely require society reducing global emissions of greenhouse gases to levels that are significantly below present day values. As the magnitude of global warming is strongly determined by cumulative emissions of long-lived greenhouse gases, and notably CO₂ (Allen *et al* 2009, Meinshausen *et al* 2009), then emissions of such gases will have to reduce to near zero. This eventual near-complete decarbonization has been noted by other authors (e.g. Matthews and Caldeira 2008, Solomon *et al* 2009, Lowe *et al* 2009). Research indicates that having a high chance of limiting global to 2 °C requires greenhouse gas emissions to peak within the next couple of decades and then decline with significant and lasting rates of reduction (e.g. Wigley *et al* 1996, House *et al* 2008, IPCC 2007 (their p 15)). Emissions reductions suggested by policymakers are often expressed as target emissions at specific dates in the future, with years 2020 and 2050 receiving particular mention (European Council 2007, G8 2008, UNFCCC 2010). Year 2020 can be noted as representing a short-term aim. Year 2050 is sufficiently far ahead that it can be regarded that many current technologies will have reached the end of their life-cycle and new technologies may be available, thus setting a roadmap for longer-term ambition. There remains uncertainty in the magnitude of key climate processes and hence representation in quantitative models. For any suggested future emissions trajectory of greenhouse gases, assessments of whether it avoids key temperature thresholds such as 2 °C should ideally be presented in terms of probabilities.

There are already studies analysing the link between mitigation options and future climate states. Kallbekken and Rive (2007) use a simple climate model to study the impact of delaying emission reductions. Their multi-gas treatment (CO₂, non-CO₂ greenhouse gases and aerosols) moves forward capturing of uncertainty by sampling a range of climate sensitivities, but does not represent uncertainty in climate–carbon cycle feedbacks. The authors find that a 20 yr delay in reducing emissions leads to the requirement of a 5–11 times greater rate of emissions reduction to stay below identical levels of warming. Similarly Vaughan *et al* (2009) examine the issue of delay, and use a more comprehensive range of scenarios, although they only consider CO₂ and do not focus on treating climate model uncertainties. They find (their figure 4(b)) that to achieve no more than 2 °C of warming requires either rates of emission reduction in excess of 5% yr⁻¹, or, action (i.e. deviation from business-as-usual emissions) to have begun before year 2010. If a period of

‘overshoot’ in temperature lasting many decades is permitted and the requirement is only to keep long-term stabilization temperature to no more than 2 °C, then emission reductions just under 3% per annum would be viable. However, again these would have to start with immediate effect (they cite year 2010 as initializing such reductions). The possibility of emissions being able to peak much later in the century than year 2020 and still limit warming to target levels is explored by O’Neill *et al* (2010). They find that this might be possible, but it relies on potentially unachievable mitigation actions later in the century.

Ranger *et al* (2012) examine year 2020 emissions ranges compatible with a 2 °C warming target for alternative scenarios. They consider two different aerosol forcing assumptions to account for uncertainty in this contribution. For ‘high’ sulfate aerosol emissions, this range extended up to 54 gigatonnes of CO₂ equivalent emissions (GtCO₂e yr⁻¹), but for a lower aerosol emission scenario and thereby ‘masking’ less global warming, this reduced to 48 GtCO₂e yr⁻¹. Ranger *et al* (2012) find as might be expected, being near the top of the range in 2020 requires emissions to fall to lower values in 2050 compared to scenarios with lower 2020 emissions, what they refer to as a ‘reversed window’.

Others have focused on stabilization at different CO₂ equivalent (CO₂e; ppm) concentrations. A 450 ppm CO₂e stabilization level can be associated with a long-term equilibrium temperature change of 2 °C, using a best estimate for equilibrium climate sensitivity of 3 °C (Meehl *et al* 2007). Using an integrated assessment modelling framework, Den Elzen *et al* (2007) concluded that achieving such a stabilization level was only technically feasible if atmospheric concentrations were allowed to temporarily overshoot before stabilization. Even this would require global CO₂e emissions in 2020 to be no more than 0–25% above 1990 levels, depending on the choice of baseline emissions, and 25–60% below 1990 levels by year 2050.

Here we examine the global warming implications of a particularly large range of potential future emission trajectories, and so advancing on, for instance, Meinshausen *et al* (2009). We adopt a warming ‘target’-based approach by considering the year 2020 and 2050 total greenhouse gas emissions that are consistent with limiting the risk of exceeding 2 °C at any point before year 2500. Hence for this initial analysis, although of importance, we do not include the technical, economic or political feasibility of proposed emissions reductions, nor do we consider the different breakdowns of emissions by sector or by different geographical regions (e.g. Anderson and Bows 2008, 2011). We show how choices made for the 2020 emissions targets have consequences for the allowable range at 2050 and beyond. Particular emphasis is placed on embedding our analysis in a probabilistic framework based on current uncertainties associated with Earth system science. Results are presented in the context of the emission reduction pledges given in the annex to the recent Copenhagen Accord.

2. Methods

2.1. Climate modelling

An initial set of around 150 different emissions trajectories drive a core set of simulations. For each trajectory, ensembles of simulations using a variant of the MAGICC climate model provide a probability density function for the time series of global average temperature rise. The MAGICC model has its origins in an upwelling diffusion energy balance model of Hoffert *et al* (1980) with further development by Wigley and Raper (1992, 2001) including the depiction of the global carbon cycle by Wigley (1993). It has been the basis for many climate change projections, including contributions to all the IPCC WG1 assessments to date (e.g. Cubasch *et al* 2001, Meehl *et al* 2007). Based on the version in Wigley and Raper (2001), the variant of MAGICC we use samples identically to Lowe *et al* (2009) uncertainty in the three large scale bulk parameters of (i) equilibrium climate sensitivity, (ii) ocean diffusivity and (iii) a measure of the climate–carbon cycle feedback. Each parameter is assigned nine potential values along with an associated probability. We assume parameter values are independent and for any parameter triplet an overall probability can be assigned by multiplying together the individual probabilities. (This assumption is worthy of future investigation to see how contemporary measurements may constrain climate models further and potentially yield a joint distribution.) All triplet parameter possibilities are considered, corresponding to 729 different simulations. The MAGICC model is a simple climate model so processes are more highly parameterized than in full general circulation models (GCMs) used by many climate modelling centres. Whilst losing geographical information, the simplifications enable large numbers of simulations to be performed, which here are the 150 core trajectories for 729 parameterizations. However even this is time consuming and a method is described in section 3 to interpolate our core scenario results to a well-populated continuum of possible trajectories.

The uncertainty distribution for climate sensitivity is from Murphy *et al* (2004), based on results from an ensemble of more complex models weighted against observational datasets from the recent past. This can be compared to the compilations of Meehl *et al* (2007; their Box 10.2, figure 1) and Meinshausen *et al* (2009; their figure 1(a)), comprising 11 and 20 examples respectively. The median of the Murphy distribution is 3.25 K and on the high side of the spread of median values in the literature. However this distribution is less asymmetric than others as a result of their sampling design, lacking the ‘fat tail’ characteristic of other distributions (Roe and Baker 2007, Knutti and Hegerl 2008). The influence of oceanic diffusion parameterization on ability to achieve temperature stabilization is highlighted by Johansson (2011). Here, uncertainty in ocean diffusivity is estimated by fitting a lognormal distribution to effective values of that quantity, derived from different atmosphere–ocean GCMs (AOGCMs) (Cubasch *et al* 2001; their table 9 A1). The climate–carbon cycle feedback uncertainty is estimated by a normal

distribution based on the MAGICC fit to the C⁴MIP ensemble (Friedlingstein *et al* 2006).

2.2. Specifying the target emission trajectories

Anthropogenic emissions of greenhouse gases and aerosol precursors are the basis of our trajectory generation, for which climate responses with uncertainty bounds are estimated. Around 150 core emission trajectories, defined by four features or parameters, are inputs to the MAGICC climate model. We set (i) two possible ‘baseline’ emissions trajectories between 1990 and the time of the start of mitigation measures, (ii) years of peak emissions, 2016, 2020, 2025 and 2030, (iii) post-peak CO₂ emission reduction rates covering a range of 1, 2, 3, 4 or 5% reduction per annum and with a small number up to 10% and (iv) a long-term emissions floor defined as ‘zero’, ‘low’, ‘medium’ and ‘high’ (0, 6, 11 and 16 GtCO₂e yr^{−1} respectively). Here baseline emissions are defined as an estimate of historical emissions up to year 2000, followed by a ‘Business-as-Usual’ scenario which assumes no explicit climate mitigation policy. CO₂e emissions are calculated using the 100 yr global warming potential values in Schimel *et al* (1996). We adopt the 100 yr global warming potential as our metric to aggregate different greenhouse gas emissions, given it is the one currently most used in international discussions on climate policy. Included in this aggregation are carbon dioxide, methane, nitrous oxide and the fluorinated gases included in the Kyoto Protocol. Other metrics exist which are more tailored towards a temperature based target; see for instance Shine *et al* (2005) and Smith *et al* (2012). We make the key assumption that non-CO₂ radiatively active gases follow slightly different assumptions regarding reduction rates, but in general they are either equal to, or a little less, than that prescribed for CO₂. The ratios between emissions of non-CO₂ greenhouse gases and CO₂ are similar to those implicit in the SRES B1 scenario (Nakićenović and Swart 2000); with emissions of gases moving together, the use of a single aggregating metric becomes more valid. Much more detail and rationale behind the scenario generation is given in supplementary information (available at stacks.iop.org/ERL/7/014039/mmedia). This includes describing our treatment of aerosols, where the main feature is that SO₂ emissions are also related to CO₂ emissions. This might be a reasonable first-order approximation given co-generating sources.

The emissions floor value represents the concept of there being a component of emissions that is difficult or impossible to remove for society to function, and we assume it is composed of carbon dioxide, methane and nitrous oxide. We consider two baselines as there remains significant uncertainty in the recent historical emissions, and predominantly in land use change emissions. Recent best estimates of emissions (Manning *et al* 2010) suggest that, considering across the period years 2000–2010, we are currently on a trajectory that falls just below the SRES A1B scenario (Nakićenović and Swart 2000). To account for this, we consider both the A1B scenario and a second scenario with an emissions growth rate of just 1% below, which we call A1B-1%.

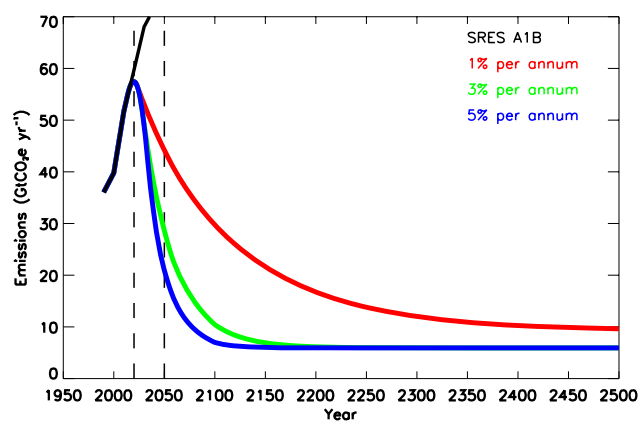


Figure 1. Three sample CO₂-equivalent emissions profiles corresponding to peak emissions in year 2020, followed by year-on-year reductions of 1%, 3% and 5%, heading to an eventual floor of 6 GtCO₂e yr⁻¹. Also shown are the SRES A1B baseline emissions. The years of 2020 and 2050 are marked as vertical lines.

Peak emissions occur seven years after deviation from the baselines. In figure 1, we illustrate three profiles where the baseline emissions trajectory is SRES A1B, peak emissions are in year 2020, subsequent rates of reduction are 1, 3 and 5% and the eventual emissions floor is 6 GtCO₂e yr⁻¹.

3. Results

3.1. Climate model projections

We present findings from our core simulations with the MAGICC model. Figure 2 shows the relationship between the median peak temperature during years 2000–2500 and corresponding CO₂-equivalent emissions for years 2020 and 2050. Emissions in year 2050 provide a better indicator of peak warming than in 2020, as is evident in the spread along the vertical axis of figure 2; a similar result is presented in Bowerman *et al* (2011). We investigate the reportedly strong relationship between cumulative emissions and the probability of crossing a peak warming threshold such as 2 °C (Allen *et al* 2009, Meinshausen *et al* 2009). For each trajectory, emissions are summed for years 2000–2500, and peak warming values recorded on this timescale for each ensemble member associated with that trajectory. Figure 3 shows a tight link between the probability of exceeding 2 °C and cumulative CO₂e emissions, despite the broad range of parameters that define the emissions profiles. Due to the assumed correlations between changes in non-CO₂ greenhouse gases emissions and those for CO₂, then such probabilities could also be tightly related to cumulative emissions of carbon dioxide only. This is demonstrated in figure S1 of the supplementary information (available at stacks.iop.org/ERL/7/014039/mmedia), where the two cumulative calculations (of CO₂e and CO₂ only) are compared. Figure 3 does separate out a strong dependence on emissions floor, due to the longer limits on our cumulative emission integrations (Bowerman *et al* 2011 integrate to 2200 only to remove this dependence). In figure 3, only two emissions floors (0 and 6 GtCO₂e

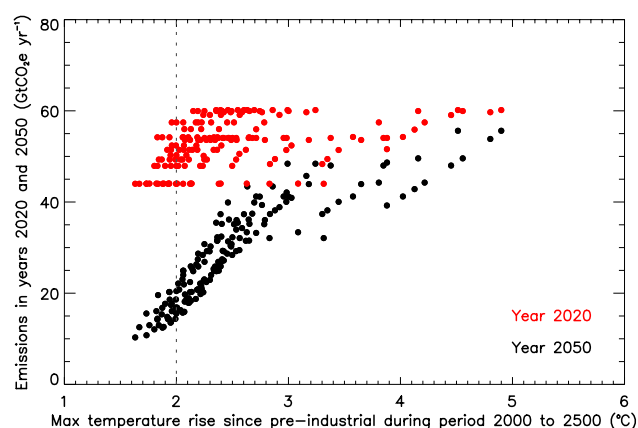


Figure 2. Emissions in years 2020 (red dots) and 2050 (black dots) for each core emission trajectory with zero or low floors. This is plotted against the median in maximum temperature rise in period 2000–2500, derived from the probabilistic ensembles for each core trajectory. The vertical dashed line corresponds to 2 °C global warming.

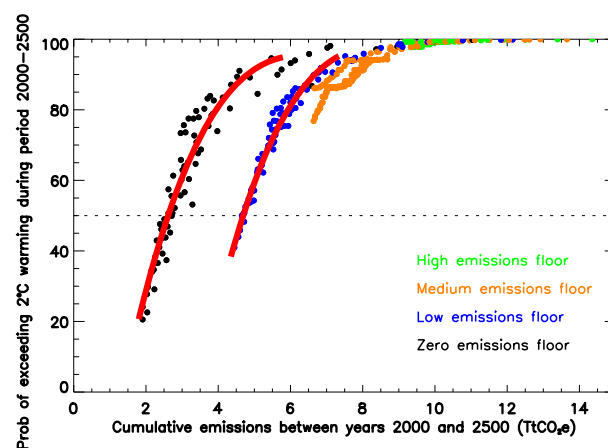


Figure 3. The probability of exceeding 2 °C of global warming since pre-industrial times at any point during the period 2000–2500, as a function of cumulative emissions between years 2000 and 2500 (in units of trillion i.e. 10¹² tonnes of CO₂e). This is for the core emissions profiles. The different colours distinguish the long-term emissions floors, high (16 GtCO₂e yr⁻¹), medium (11 GtCO₂e yr⁻¹), low (6 GtCO₂e yr⁻¹) and zero (0 GtCO₂e yr⁻¹). The red line is the curve of best fit for the low and zero floors. (Additional available core emission scenarios following a B2 SRES baseline emissions scenario were also included). The 50% probability of staying below the 2 °C threshold is marked as the dashed line.

are capable of reducing the probability of exceeding two degrees to 50% or less for at least some of simulations. For the high floors, in general temperatures just continue to rise, crossing the 2 °C threshold. From our fitted regression curves, a 50% probability of temperature rise not exceeding 2 °C before year 2500 corresponds to cumulative emissions of 2.63 trillion tCO₂e (or 0.72 TtC) for a zero emissions floor and 4.69 TtCO₂e (1.28 TtC) for a low emissions floor, and with the higher latter value predominantly due to the long time-integration of the non-zero floor.

3.2. The link between year 2020 and 2050 emissions and the probability of remaining below two degrees of global warming

Tight correlations evident in figure 3 between cumulative emissions and probability of exceeding a 2 °C warming level (for a given emissions floor) allow interpolation from the core trajectories, as simulated with the MAGICC climate model, over to many other emissions trajectories. For any emissions trajectory and floor defined by parameter values in section 2.2, the probability of exceeding the 2 °C threshold can be related to calculation of cumulative total emissions. Such probabilities are provided by the red best fit curves of figure 3. This is now exploited to give a comprehensive analysis of how attributes of different future emissions trajectories link to the 2 °C threshold in global warming.

We first consider emissions trajectories with a zero emissions floor, and the A1B and A1B-1% baselines for present day. Figure 4 shows the combinations of emissions in years 2020 and 2050 that are possible to keep warming below 2 °C, all for at least a 50% probability and for trajectory parameters in the bounds outlined above. For different year 2020 and 2050 emissions, the top row of figure 4 provides values of post-peak reduction rate and the middle row shows CO₂e emission peak year. We can refer to these as emission ‘constraints’. The bottom row of figure 4 presents for different values of 2020 and 2050 emissions, the probability of staying below 2 °C. These latter values could be referred to as emissions ‘consequences’. Figure 5 is identical to figure 4, except that it corresponds to an emissions floor of 6 GtCO₂e yr⁻¹.

A growing number of nations, whose combined emissions cover more than 80% of the total, have pledged to make voluntary reductions in their emissions by 2020. This is particularly true following the COP15 negotiations at Copenhagen in year 2009 (UNFCCC 2009). Placed as small vertical bars on the year 2020 axes in our panels of figure 4 are lower (‘L’) and upper (‘U’) interpretations of the integrated pledges made for emissions and as detailed in the appendices of the Copenhagen Accord. The value ‘L’ presented is 46.7 GtCO₂e, and this is the lower 20% of the lower estimates. The absolute lowest value possible from interpreting the pledges is 45.2 GtCO₂e. The value ‘U’ is 57.1 GtCO₂e and this is the upper 80% of such upper estimates. The highest possible value is 60.6 GtCO₂e. The divide between upper and lower estimates reflects issues such as whether an individual country’s pledges are conditional on action from the rest of the world, technological transfer or finance, or action on land use and forestry emissions (UNEP 2010).

Figures 4 and 5 provide a ‘look-up chart’ which can be utilized in a variety of ways. In one application, it links prescribed year 2020 and 2050 emissions with requirements to achieve these emissions in terms of year of peak emissions, emissions reduction rate and floor, and what is gained i.e. percentage chance of remaining below 2 °C. White space indicates where year 2020 and 2050 values are not possible with a 50% or higher probability of staying below 2 °C of

global warming (e.g. very high 2050 emissions), or where the values are beyond the parameter bounds describing possible emissions trajectories (e.g. very low 2050 emissions).

The diagrams can be used in reverse where constraints are prescribed (e.g. a particular level of decarbonization and peak year), and from this implications for emissions in 2020 and 2050, along with probability of remaining below the 2 °C target, can be read off. Another use of the diagrams is to prescribe different acceptable percentage levels of risk of crossing the 2 °C threshold, and determining flexibility in the balance between year 2020 and 2050 emissions. This flexibility becomes a single aspiration for years 2020 and 2050 by stipulation of what is feasible for one of the constraints (e.g. decarbonization rate) as more information on that becomes available.

4. Discussion and conclusions

We relate year 2020 and 2050 emissions to attributes of potential future emissions trajectories and associated probabilities of exceeding the 2 °C threshold of global warming since pre-industrial times. For prescribed long-term future floor and contemporary baseline emissions, supplying values for 2020 and 2050 emissions determines the year of peak emissions, subsequent decarbonization rate and probability of staying below two degrees of warming out to year 2500.

To remain below 2 °C in global warming, emissions must peak and soon, followed by significant rates of decarbonization. Our analysis has encapsulated uncertainty in aspects of the Earth system, thereby generating probabilistic estimates. Across all simulations, we find the slowest rate of decarbonization consistent with a 50% chance of exceeding 2 °C to be slightly below 3% per annum, where this corresponds to the specific case of emissions peaking by year 2014 (so in fact deviation from business-as-usual would have to have already started) and a zero emissions floor. For later peaking, a non-zero emissions floor, a higher certainty of remaining below the 2 °C threshold, or any combination of these, then higher reduction rates are required. The difficulty of implementing higher decarbonization rates cannot be underestimated. Le Quere *et al* (2009) and others note the continuing strong correlation between global domestic product (GDP) and emissions.

The presence of a non-zero emissions floor significantly reduces the emissions in both 2020 and 2050 compatible with limiting warming to 2 °C with at least 50% probability. Considering the A1B-1% scenario and only post-emission peak reduction rates of up to 5% yr⁻¹, the presence of an emission floor of 6 GtCO₂e yr⁻¹ reduces the maximum allowable 2020 emissions from around 54 GtCO₂e yr⁻¹ to around 47 GtCO₂e yr⁻¹, and corresponding 2050 emissions from 20 GtCO₂e yr⁻¹ to around 15 GtCO₂e yr⁻¹. It also suggests that a slightly earlier peak in emissions might be needed and achieving lower probabilities of crossing the two-degree threshold (e.g. less than 30%) becomes impossible. This suggests an importance to estimating the extent to which emissions floors might be eliminated through new technology, as their presence significantly reduces the

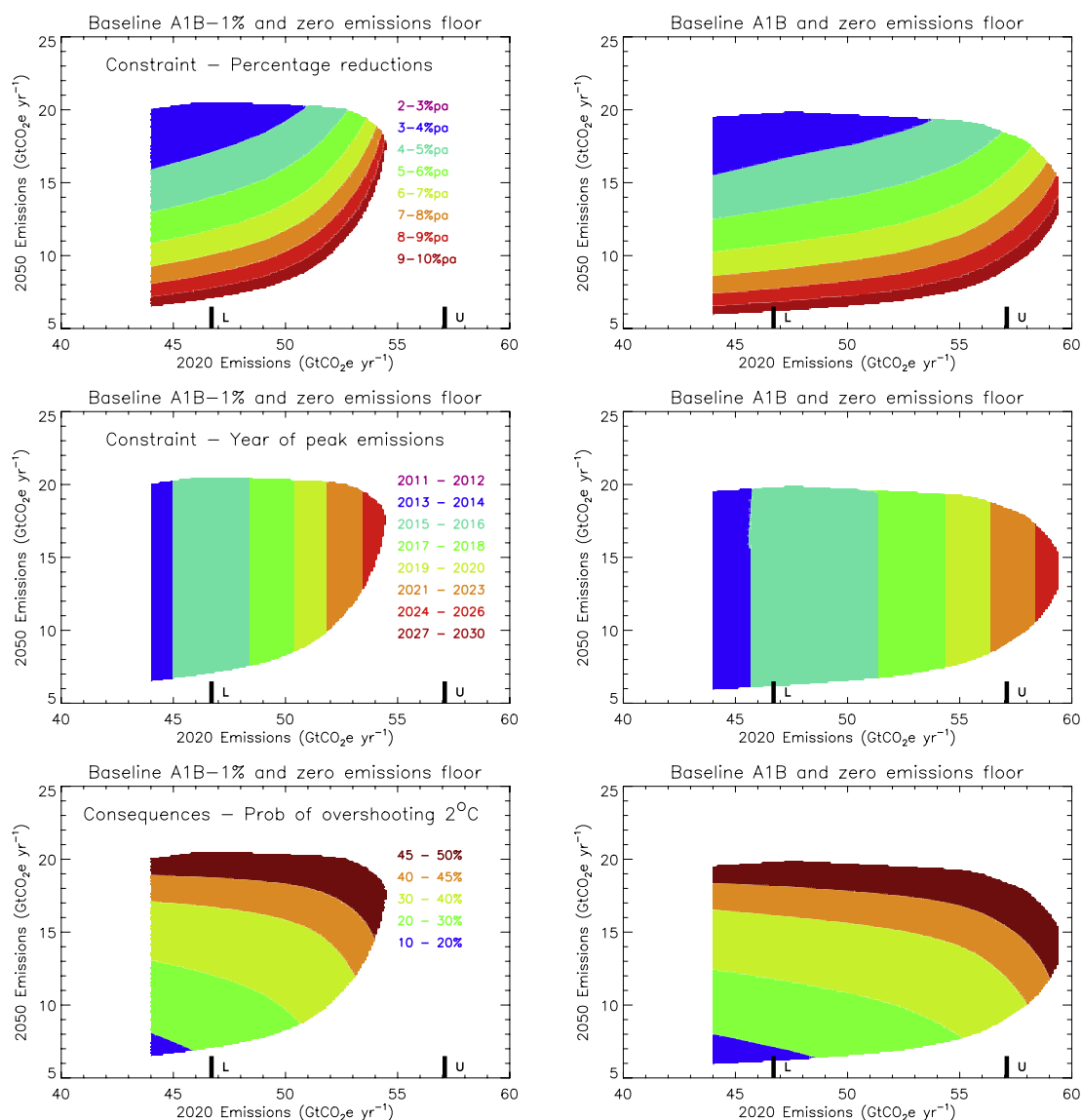


Figure 4. For two different baseline scenarios (A1B-1% left-hand column and A1B right-hand column), and all for a zero long-term emissions floor, presented are simultaneous constraints on emission trajectory shapes and consequences in terms of probabilities of staying below the 2 °C threshold. This is all for different emissions in years 2020 (x-axes) and 2050 (y-axes). The values of 2020 and 2050 emissions where a solution exists (i.e. there is colour in the figures) all correspond to the probability of remaining below two degrees of global warming as being 50% or greater, and where parameters defining trajectories profiles fall within the bounds given in the main body of text. The top panels show the post-peak CO₂ emissions reduction rates (%), the middle panels show the year of peak emissions and the bottom panels show the probability of remaining below two degrees global warming up to year 2500. The 'L' and 'U' ticks indicate lower and upper bounds of year 2020 emissions assuming the Copenhagen Accord pledges are met and based on our interpretation.

room for manoeuvre even in the near term. We also find a strong dependence on current emissions levels, and better understanding is required to determine these more precisely, and where most uncertainty is associated with land use practises. Higher contemporary emissions correspond to lower year 2050 emissions to achieve similar probabilities of staying below the two-degree threshold.

We place our analysis in the context of the Copenhagen pledges (UNFCCC 2009). Complex linkages between the pledges of individual countries means there remains uncertainty in their implications for total emissions in year 2020. From the geometry allowed in our profiles, for the lower A1B-1% simulations, then upper pledge values (i.e. smaller pledged reductions) will not be attained anyway. Even if

society is following the higher A1B profile, then across the possible pledge range, we find available solutions in order to stay below 2 °C of global warming with a 50% chance or more. However only achieving the upper part of 2020 emissions range in terms of pledge interpretation (i.e. higher year 2020 emissions) requires larger subsequent rates of reduction, lower year 2050 emissions and potentially lower floors to achieve the same probability of remaining below the 2 °C threshold.

The precise values presented in this letter's visualization of keeping global warming below 2 °C will be refined as better understanding of the climate system becomes available. We have used one modelling framework, a single climate sensitivity distribution and there remains

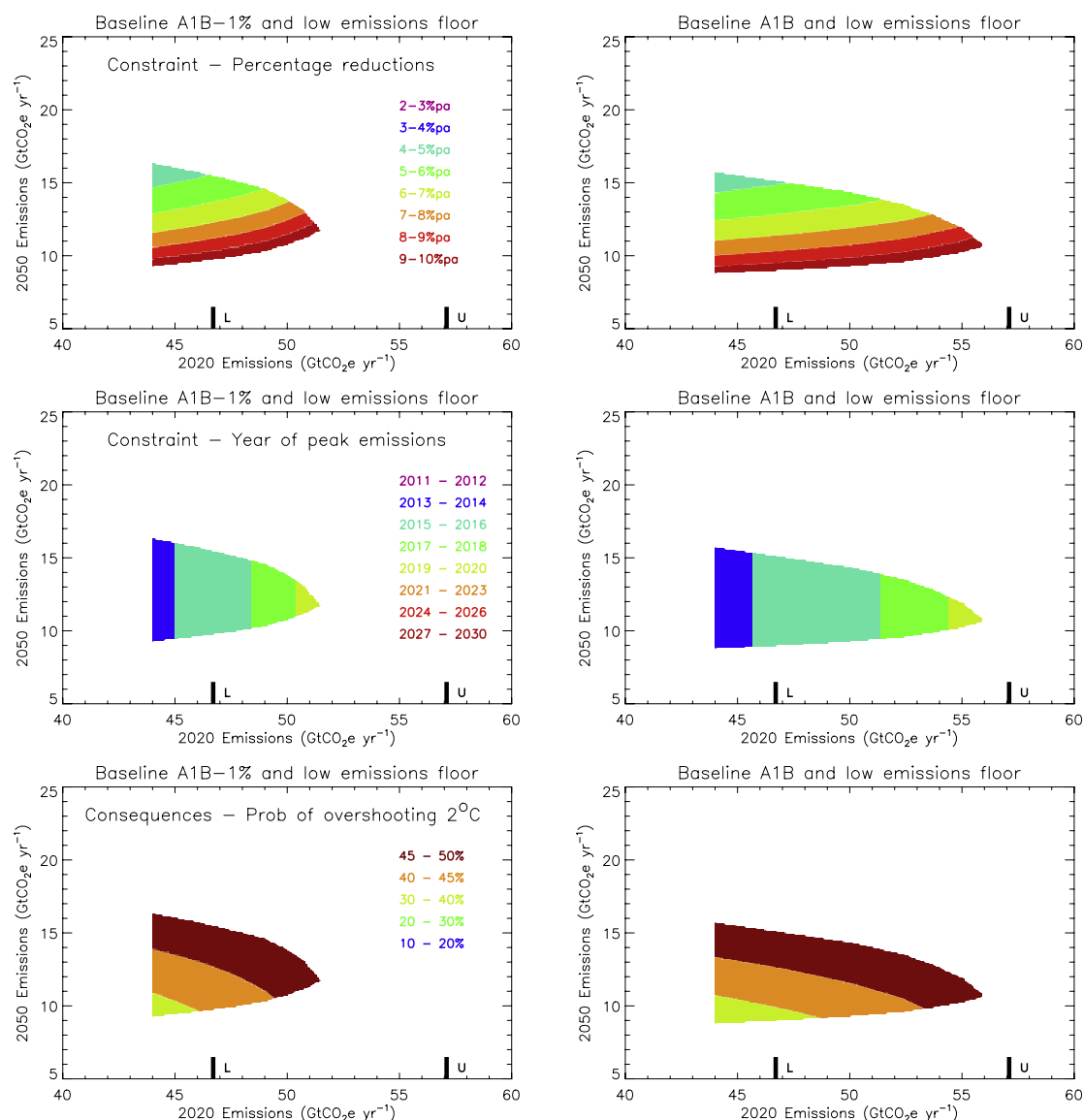


Figure 5. Identical panels to those present in figure 4, except that here all correspond to an emissions floor of 6 GtCO₂e yr⁻¹.

significant uncertainty in present day and thus future magnitude of aerosol radiative forcing (e.g. Stott *et al* 2008). In particular, we need to consider how sensitive our results are to assumptions (supplementary information available at stacks.iop.org/ERL/7/014039/mmedia) regarding future near-constant ratios between emissions of different greenhouse gases, and between these and aerosols. The CO₂e numbers reported here to achieve a two-degree warming limit, for a given probability, do not include (but are nevertheless dependent on) the assumed aerosol emissions. Despite these uncertainties, we believe the main messages of this analysis to be robust, providing a broad indication as to what is required for year 2020 and 2050 emissions to remain below two degrees of global warming for different levels of confidence.

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