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Emission pathways consistent with a 2 °C global temperature limit

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In recent years, international climate policy has increasingly focused on limiting temperature rise, as opposed to achieving greenhouse-gas-concentration-related objectives. The agreements reached at the United Nations Framework Convention on Climate Change conference in Cancun in 2010 recognize that countries should take urgent action to limit the increase in global average temperature to less than 2 °C relative to pre-industrial levels[1]. If this is to be achieved, policymakers need robust information about the amounts of future greenhouse-gas emissions that are consistent with such temperature limits. This, in turn, requires an understanding of both the technical and economic implications of reducing emissions and the processes that link emissions to temperature. Here we consider both of these aspects by reanalysing a large set of published emission scenarios from integrated assessment models in a risk-based climate modelling framework. We find that in the set of scenarios with a 'likely' (greater than 66%) chance of staying below 2 °C, emissions peak between 2010 and 2020 and fall to a median level of 44 Gt of CO_2 equivalent in 2020 (compared with estimated median emissions across the scenario set of 48 Gt of CO_2 equivalent in 2010). Our analysis confirms that if the mechanisms needed to enable an early peak in global emissions followed by steep reductions are not put in place, there is a significant risk that the 2 °C target will not be achieved.

Cumulative emissions of long-lived greenhouse gases (GHGs) approximately define the temperature response of the climate system at timescales of centuries to millennia[2–4] because a significant fraction of CO_2 emissions, the dominant anthropogenic GHG, is removed very slowly from the atmosphere[5,6]. The temperature response will therefore continue, even when global emissions return to zero, or when concentrations are stabilized[6,7]. Cumulative emissions provide very little information on the technical feasibility and cost implications of following a particular 'emissions pathway', information that is needed for policymakers who are deciding now on emissions goals for the coming decades. Path-dependent assessments, such as the United Nations Environment Programme's *The Emissions Gap Report*[8], are therefore highly policy-relevant. This work extends the pathway analysis of that report (see Supplementary Information).

The Cancun Agreements refer to holding global mean temperature increase below 2 °C. Therefore, we do not allow a temperature overshoot in this study, although concentrations may temporarily overshoot a level that in equilibrium would lead to an exceedance of the temperature limit. There is increasing evidence from recent studies[7,9,10] that a decline of temperature might be unlikely on timescales relevant to human societies in the absence of strongly negative emissions. The slow ocean mixing that delays warming due to anthropogenic radiative forcing at present would also limit the amount of cooling for many decades to centuries[9–11].

Scenarios developed by integrated assessment models (IAMs) represent analyses of how society could evolve given assumed constraints of feasibility. In general, 'feasibility' encompasses technological, economic, political and social factors. IAMs account for some of these factors by assuming a set of mitigation technologies, constraining their potential and the rate at which these technologies can be introduced, amongst other things. Examples of such constraints include assumptions about the maximum feasible technology penetration rates, maximum cost, constraints on the use of renewables based on their intermittency and a maximum speed of specific system changes. Societal and political factors have typically received only limited attention: for instance, nearly all mitigation scenarios assume full participation of all regions in global mitigation efforts.

Scenarios from different IAMs consistent with different policy targets have been compared in previous studies[12,13]. Most of these focus on optimal (least-cost) pathways to achieve GHG concentration stabilization. Only recently, modelling comparison studies[12] have started focusing on second-best scenarios, which assume limited/delayed international participation of countries and/or reduced technology availability implying delayed emission reductions. The range in IAM outcomes for similar targets is broad, and reflects prevailing uncertainties captured by different methods and underlying assumptions[12,14,15]. Considering the combined impact on mitigation targets of both climate and technical and economic constraints and uncertainties has thus far received little attention.

Here we present a scenario reanalysis focusing on temperature targets. We use the carbon-cycle and climate model MAGICC6 (ref. 16), constrained by historical observations, to obtain estimates

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Table 1 | Overview of pathway characteristics of emission pathways that limit global average temperature increase to below 2 °C relative to pre-industrial levels during the twenty-first century.

	Number of pathways	Peaking decade* (2000 + year)	Total GHG emissions in 2020 (Gt CO_2e)	Average industrial CO_2 post-peak reduction rates† (percentage of 2000 emissions per year)
'Very likely' chance (>90%) of staying below 2 °C during twenty-first century‡				
Without global net negative industrial CO_2 emissions	0	—	—	—
With global net negative industrial CO_2 emissions	3	10(—[10]—)15	41(—[43]—)44	3.2(—[3.3]—)3.3
All pathways	3	10(—[10]—)15	41(—[43]—)44	3.2(—[3.3]—)3.3
'Likely' chance (>66%) of staying below 2 °C during twenty-first century				
Without global net negative industrial CO_2 emissions	14	10(10[10]10)20	21(26[42]45)48	0(1.0[2.3]3.3)3.6
With global net negative industrial CO_2 emissions	12	10(10[10]15)15	41(41[44]46)48	1.5(1.7[3.0]3.5)3.8
All pathways	26	10(10[10]15)20	21(31[44]46)48	0(1.5[2.7]3.4)3.8
'At least fifty-fifty' chance (>50%) of staying below 2 °C during twenty-first century				
Without global net negative industrial CO_2 emissions	20	10(10[10]15)20	21(28[44]47)48	0(1.3[2.4]3.1)3.6
With global net negative industrial CO_2 emissions	19	10(10[10]20)30	41(42[45]48)50	1.2(1.7[3.0]3.6)5.9
All pathways	39	10(10[10]15)30	21(38[44]47)50	0(1.5[2.7]3.5)5.9

Data are provided for three probability options: a 'very likely' (greater than 90%), a 'likely' (greater than 66%) or 'at least fifty-fifty' (greater than 50%) chance.
Format: minimum(15%quantile[median]85%quantile)maximum. *The year given is an indication of the middle of the decade in which the peaking occurs in the scenarios. †Being relative to constant 2000 emissions, these reduction rates differ from exponential reduction rates (see Methods). ‡Owing to the low number of pathways, only minimum, median and maximum values are given for the 'very likely' option.

of future atmospheric GHG concentrations and transient temperatures (see Methods). This approach eliminates the uncertainty due to differing climate representations within the individual IAM studies[17]. We compiled a set of 193 emissions pathways from the literature (see Methods and Supplementary Information). Of this set, roughly one third represents baseline scenarios (that is, possible developments in the absence of climate policy intervention) and the remainder represents emission mitigation scenarios.

Owing to the uncertainty in our quantitative understanding of the climate system and carbon-cycle response to emissions, the projected results can be defined in terms of a probability of staying below a given temperature target. The choice of which target and with which probability it is to be reached can be informed by science but is fundamentally a political question depending on risk and value judgements. Policymakers in Cancun did not specify such a probability, neither quantitatively nor qualitatively. To cover a range of possible choices, we evaluate pathways for three options: a 'very likely' (greater than 90%), a 'likely' (greater than 66%) and an 'at least fifty-fifty' (greater than 50%) probability throughout the twenty-first century (see Methods). Pathways with a 'very likely' 2 °C probability are a subset of pathways with a 'likely' probability, which are in turn a subset of the pathways with an 'at least fifty-fifty' probability of limiting temperature increase to below 2 °C.

In our set, none of the baseline scenarios is able to limit the global temperature increase to below 2 °C. On the other hand, 3, 26 and 39 pathways have a 'very likely', 'likely' and 'at least fifty-fifty' chance to limit global temperature change to below 2 °C during the twenty-first century, respectively (Table 1, Fig. 1). In all pathways, emissions peak in the short term and decline later to stay below 2 °C. We start from estimated median 2010 emissions across our harmonized set (see Methods) of about 48 Gt of CO_2 equivalent (CO_2e). For pathways with a 'likely' chance of staying below 2 °C we find the following characteristics: median 2020 emissions are 44 Gt CO_2e, with a 15–85% quantile range of 31–46 Gt CO_2e. Most of these pathways (at least 85% of all cases) peak global emissions before 2020. After the peak, emissions decline. Still for the same pathways, median annual post-peak CO_2 reduction rates (see Methods) are around 2.7% (range 1.5–3.4%), and global total GHG emissions in 2050 show a median reduction of 45% (range 35–55%) below 1990 levels of 36.6 Gt CO_2e.

Besides a 2 °C limit, the Cancun Agreements furthermore include a commitment to review and consider strengthening the long-term goal, particularly in relation to a 1.5 °C limit. No ensemble member (including even the most stringent mitigation scenarios) limits warming to less than 1.5 °C throughout the entire century for any of the probability options. However, some scenarios in our set bring warming back below 1.5 °C by 2100: a first scenario (from 'POLES' in ref. 13) does so with a probability of about 50%, and a second scenario (from 'MERGE' in ref. 13) with a 'likely' chance (>66%).

An important difference[14] is noted between pathways that do not show global CO_2 emissions from energy and industry to become negative compared with those that do. Net negative emissions from the energy and industry sector may be possible through the application of a combination of capture and geological storage[18] of CO_2 (CCS) and bio-energy[19] (BECCS). In the pathways with no negative emissions, the median 2020 values for the 'likely' option are 2 Gt CO_2e lower at 42 Gt CO_2e (Table 1). Pathways that have net negative emissions (28 in total) feature higher rates of post-peak emission reductions while not exhibiting significant differences for the peak period. An in-depth analysis of the influence of BECCS on the

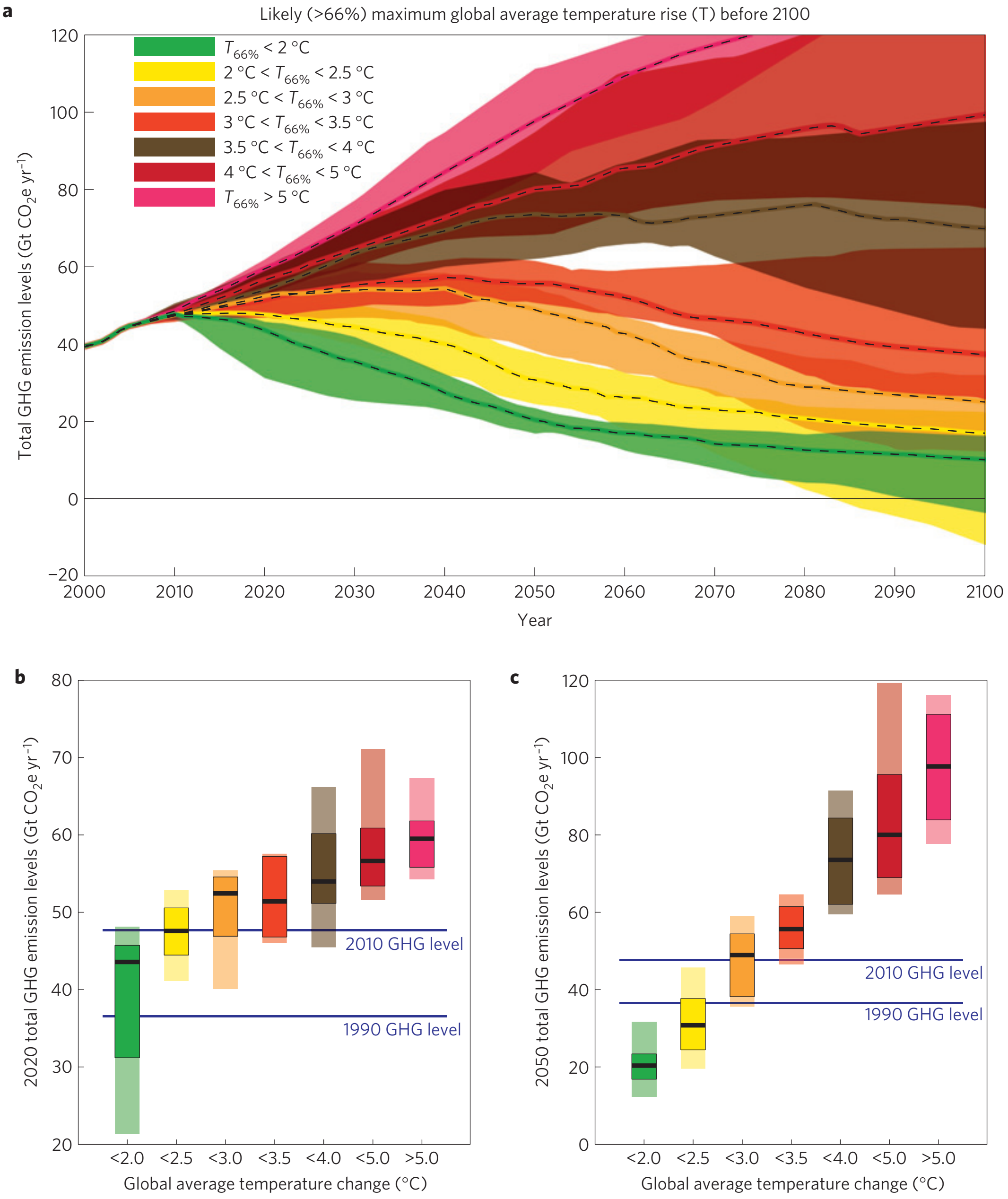

Figure 1 | Emission ranges of published IAM scenarios, colour coded as a function of the likely (greater than 66% probability) avoided global average temperature increase. a, 15–85% quantile ranges over time of global total GHG emissions of pathway sets consistent with a given temperature limit during the twenty-first century. Colour coding defines the respective temperature limit per pathway set. Black dashed lines show the median for each respective pathway set. **b**,**c**, 2020 (**b**) and 2050 (**c**) time slices of global total emissions consistent with a temperature limit during the twenty-first century. Shaded areas represent the minimum–maximum ranges; the coloured bounded rectangles the 15–85% quantile ranges and the thick black horizontal lines the median values for each temperature level, respectively. Horizontal blue lines represent median 1990 and 2010 emissions. Ranges for the other probability options (>90% and >50%) and time slices are given in Supplementary Figs S1–S5.

global peak of emissions is not possible with the available scenarios and would require specifically designed experiments that address this question.

Weakening the stringency of the 2 °C limit and accepting a lower chance of success (at least 50% instead of 66% probability), slightly shifts the 15–85% quantile range of scenarios in 2020 to 38–47 Gt CO$_2$e (the median remains at 44 Gt CO$_2$e). The peaking period remains during the present decade (precision-limited by the decadal-resolution data from the IAMs) and the median post-peak emission reduction rates are virtually the same as for the 'likely' case in more than 85% of the cases. Finally, the three pathways with a 'very likely' (greater than 90%) chance of success show a peak during this decade, 2020 emissions not exceeding 44 Gt CO$_2$e and post-peak reduction rates that are higher than the medians from the other cases. These three pathways have negative emissions.

Atmospheric CO$_2$ and CO$_2$e concentrations in 2100 of the pathways 'likely' consistent with 2 °C (Table 2) are around 425 ppm CO$_2$ (range 415–460) and 465 ppm CO$_2$e (range 435–475), respectively. Pathways consistent with 2 °C with a 'likely' or 'fifty-fifty' chance have peaked CO$_2$ concentrations during the twenty-first century (see Methods) in about 30 and 40% of the cases, respectively. CO$_2$-equivalent concentrations peaked in about 40% of the cases for both probability options. If scenarios do not peak concentrations, they stabilize during the twenty-first century. A

Table 2 | Overview of 2020 emissions, 2100 atmospheric CO_2 and total GHG concentrations of pathways that hold global average temperature increase below a specific temperature limit.

	Number of pathways	Total GHG emissions in 2020 (Gt CO_2e)	Atmospheric concentrations in 2100	
			CO_2 (ppm CO_2)	Total GHG (ppm CO_2e)
Emission pathways with a 'likely' (>66%) probability to limit temperature increase to below:				
1.5 °C	Insufficient data	Insufficient data	Insufficient data	Insufficient data
2 °C	26	21(31[44]46)48	375(412[423]457)468	400(436[463]476)486
2.5 °C	46	41(44[48]51)53	376(416[490]506)542	422(472[526]554)557
3 °C	45	40(47[52]55)55	477(501[542]574)616	554(561[609]636)645
3.5 °C	22	46(47[51]57)58	540(562[602]659)709	647(649[669]751)775
4 °C	18	45(51[54]60)66	649(661[726]811)890	759(782[833]869)939
5 °C	19	52(53[57]61)71	678(746[817]958)1104	851(922[993]1101)1134
Above 5 °C	10	54(56[59]62)67	888(905[975]1046)1049	1116(1153[1207]1318)1482

Data are provided for pathways that hold temperature increase to below a given temperature limit during the twenty-first century with a 'likely' (greater than 66%) chance. Results are given for temperature bins defined by the temperature limit and its preceding limit. For example, the '3 °C' row shows characteristics for emission pathways that limit warming below 3 °C with a 'likely' chance, but above 2.5 °C. See also Fig. 1 and Supplementary Fig. S6. Data for the other probability options are presented in Supplementary Figs S3, S5, S7 and S8, and in Supplementary Tables S1 and S2. Format: minimum(15%quantile[median]85%quantile)maximum.

decline afterward is not excluded. All 'very likely' chance pathways show a peak and decline in CO_2e concentrations of GHGs. More than 70% of the 'likely' chance scenarios assume global net negative CO_2 emissions from industry and energy to achieve such peaking. Furthermore, all scenarios that would comply with a 'fifty-fifty' chance and are outside the 'likely' subset include such negative emissions.

There are a number of caveats in interpreting our results. First, by describing the 15–85% quantiles over time, the intertemporal relationship between different emission paths is masked. Although the median path can be considered as a representative evolution of emissions for 'likely' pathways, the 15 and 85% quantile paths cannot. Emissions near the 85% quantile path in the first half of the century are followed by emissions near the 15% quantile path in the second half and vice versa (see Supplementary Fig. S9).

Second, besides results from the 15–85% quantiles, results outside this range also give insights. They provide information about potential future worlds in the tails of the distributions. A few pathways[20,21] (three in total) suggest that emissions could decline globally to about 30%–40% below 1990 levels by 2020. On the other side of the spectrum, one pathway[22] peaks at 48 Gt CO_2e in 2020 owing to delayed participation and still stays below 2 °C with a 'likely' chance. Another scenario[23] shows steep emission reduction rates of 5.9% after peaking at 50 Gt CO_2e around 2030, while still having an 'at least fifty-fifty' probability to stay below 2 °C. CCS contributes massively to the mitigation portfolio in this scenario, capturing up to almost double the present global CO_2 emissions per year by 2065. For most scenarios in our set, a peak in world emissions in 2030 would be more consistent with a 'likely' chance to stay below 3 °C instead of 2 °C.

A third issue is that for many scenarios the potential for net negative global CO_2 emissions from energy and industry is a crucial factor[14]. The potential of BECCS (refs 18,19) is already included in many IAMs. However, as for other advanced technologies, BECCS has not been demonstrated on a significant scale in the real world. Concerns exist with respect to CO_2 storage potential[18] as well as with respect to competition of large-scale bio-energy systems[24] with food production, biodiversity and ecosystem services. Other negative emission technologies, such as direct air capture of CO_2, are not explicitly included in most models at present.

Fourth, our set of pathways represents scenarios that are considered feasible by IAMs. The extent to which the realization of such scenarios is plausible in the real world goes beyond techno-economic and physical constraints represented by the IAMs, and also depends highly on factors such as political circumstances and public acceptance. Our analysis of the scenario space relies on the soundness and quality of the underlying IAM studies, and does not imply any independent assessment of the feasibility of the above-mentioned factors. We also acknowledge that only a limited set of scenarios were run for the low-temperature targets discussed here, and that scenario details are often not reported when IAMs find these targets infeasible[12]. Our findings, in particular with respect to low-emissions scenarios, therefore should be interpreted as an indication of the stringency of mitigation that would need to occur to keep specific targets within reach. They should, however, not be interpreted as a comprehensive assessment of the feasibility of the required mitigation action.

Related to this, it should be noted that most of the IAM scenarios used in this study tried to find cost-effective pathways for long-term climate targets. Scenarios that would look at economically less attractive[12,25] options could feature higher and/or later peaks with steeper declines afterwards. The ensemble we used was not designed to systematically sample all possible options, but represents an 'ensemble of opportunity'[26]. Clearly, IAMs do not set 'hard laws' on the consideration of whether achieving a particular scenario is possible. They are based on modellers' assumptions about technological and economic constraints, which are subject to change. Finally, a better understanding of socio-economic impacts of regional climate change and their inclusion in IAMs might have a large influence on the medium- and long-term cost efficiency of emission pathways. As understanding evolves, it will be necessary to update assessments such as the one presented here and develop studies that address this question directly. Furthermore, the treatment of political feasibility, including the will of national governments to implement transitions to low-carbon economies, remains a big unknown.

This analysis implies that the range of published IAM scenarios in line with the goal of staying below 2 °C with a 'likely' chance would peak during this decade and have annual 2020 emissions of around 44 Gt CO_2e (range of 31–46 Gt CO_2e). Our scenario set includes hardly any scenarios that take delayed participation of regions in international carbon markets into account. However, not assuming this at present seems optimistic given the reluctance of some major emitters to join such a system. Following higher 2020 emissions and later peaking as a result of weaker early mitigation action would significantly reduce the chances of staying below 2 °C. Without a firm commitment to put in place the mechanisms to enable an early global emissions peak followed by steep reductions thereafter, there are significant risks that the 2 °C target, endorsed by so many nations, is already slipping out of reach.

Methods

We reanalysed an ensemble of 193 emission pathways from IAMs. This ensemble includes reference and mitigation pathways from model intercomparison studies (refs 12,13,27, among others, see Supplementary Table S3 for an overview of all references), as well as from other stabilization and non-intervention scenarios. All members are treated equally likely in the set.

Historical emission estimates come with a typical uncertainty range of 20–30% (ref. 28). Therefore, for each member of the ensemble, the historical emissions up to 2005 are harmonized to the historical multi-gas emission inventory developed in the framework of the representative concentration pathways[29,30] (RCPs). Emissions of each ensemble member are adjusted with a tapered scaling factor that returns to unity in 2050. This approach prevents possible amplification of negative emissions in the second half of the century[28]. When future emissions of a particular gas are missing, the multi-gas characteristics of the RCP3-PD scenario[31] are assumed, including sulphate aerosols, organic carbon, black carbon and atmospheric ozone precursors. The RCP3-PD scenario models strong environmental and climate policies. This choice is therefore consistent with our set-up to primarily analyse mitigation pathways that reduce emissions to be consistent with international temperature limits. Ozone-depleting substances controlled by the Montreal Protocol are assumed to follow a gradual phase-out during the twenty-first century.

After harmonization, six IAM pathways that show a decline or stabilization in historical emissions from 2005 to 2010 are excluded from the final ensemble. We also excluded one scenario for which insufficient detailed information about the underlying assumptions was available (as in ref. 12).

Each member of the harmonized multi-gas emission pathway ensemble is analysed probabilistically with the reduced-complexity climate system and carbon-cycle model MAGICC (ref. 16), version 6. MAGICC has been calibrated and shown to be able to reliably determine the atmospheric burden of CO_2 concentrations following high-complexity carbon-cycle models[16,32]. It is also able to project global average near-surface warming in line with estimates made by complex atmosphere–ocean general circulation models for a range of forcing scenarios, as assessed in the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change[33] (IPCC). Here it has been set up with historical constraints for observed hemispheric land/ocean temperatures and ocean heat-uptake (see Supplementary Information), emulating the C^4MIP carbon-cycle models[34] and with the same climate-sensitivity probability distribution as the ‘illustrative default case’ in ref. 2 that closely reflects IPCC estimates[33]. Herewith, the uncertainties in climate sensitivity, ocean heat-uptake and the response of the carbon-cycle to a given emissions pathway are taken into account. For each pathway, a 600-member ensemble is calculated to determine its resulting time-evolving temperature probability distribution.

We carried out a sensitivity analysis on the climate-sensitivity choice and on the assumptions regarding anthropogenic aerosols, soot and organic carbon, and found that our results are robust under those sensitivity cases (see Supplementary Information and Supplementary Table S4).

The range of results from this reanalysis of IAM pathways always refers to the median, and the 15–85% quantile range (as an approximation of the one-standard-deviation range around the mean). This provides a point of comparison with the approach in the IPCC AR4 (ref. 15). For completeness, also the minimum–maximum range is given. Total GHG emissions refer to emissions included in the Kyoto basket of GHGs, which contains carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (SF_6) (see Supplementary Information). ‘Negative CO_2 emissions’ refer to net global emissions from energy and industry, excluding land-use emissions. The ‘post-peak’ reduction rates are calculated over the period between 10 and 30 years after the peak. To allow comparison and ensure consistency with the IPCC AR4, reduction rates are computed for global CO_2 emissions from energy and industry, and relative to 2000 levels. If fewer than 10 pathways were available in a particular subset, only median, minimum and maximum values are provided. If a pathway yields atmospheric CO_2 concentrations in 2100 that are at least 5% lower than the maximum concentration during the twenty-first century, this pathway is defined to have peaked concentrations during this century. The same approach applies to the total GHG (CO_2e) concentrations.

Temperatures projections ‘relative to pre-industrial’ are calculated relative to the 1850–1875 base period.

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Author contributions

J.R., W.H., J.L., K.R., B.M., M.M. and D.P.v.V. designed the research. M.M. developed the climate model set-up. J.R. carried out the research. All authors discussed the results and contributed to writing the paper.

Additional information

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