Australian Government
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Global climate goals for temperature, concentrations, emissions and cumulative emissions

Michael R. Raupach, Ian N. Harman and Josep G. Canadell

CAWCR Technical Report No. 042

September 2011

www.cawcr.gov.au

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ISSN: 1836-019X

National Library of Australia Cataloguing-in-Publication entry

Author: Michael R. Raupach, Ian N. Harman and Josep G. Canadell

Title: Global climate goals for temperature, concentrations, emissions and cumulative emissions

ISBN: 978-1-921826-63-4 (PDF/Electronic Resource)

Series: CAWCR technical report; 42

Notes: Included bibliography references and index

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Dewey Number: 551.6994

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SUMMARY

Purpose and scope of this report

There are many different ways of quantifying the broad goal of "avoidance of dangerous human interference with the climate system", including targets for global temperature rise, radiative forcing, greenhouse gas (GHG) concentrations, GHG emissions in particular years, and cumulative GHG emissions ("carbon budgets"). The purpose of this report is to provide relationships between these different statements of a climate goal.

Broadly, the approach is to start from target for global temperature increase above preindustrial temperatures (such as two degrees Celsius or any other target, to be met with a given probability of success), then determine the radiative forcing and equivalent GHG concentrations consistent with the target, and finally the emissions consistent with the required concentrations.
Results are summarised in tabular form (Tables S1, S2 and S3). These tables are also available in a spread sheet, allowing the effects of different temperature targets and probabilities of success to be investigated interactively.

Scientific findings

This report also describes the science underpinning the relationships in Tables S1, S2 and S3, and its main implications. In summary, these are:

1. The 1996 European Union temperature target (warming of less than two degrees Centigrade above preindustrial temperatures), also adopted by the Copenhagen Accord in 2009, is associated directly with stabilisation of radiative forcing at a total CO_2 equivalent concentration (CO_2eqTot) below a median of 444 ppm, with a *likely* range of values from 387 to 540 ppm (where *likely* means an 80 per cent chance of lying in this range).

2. CO_2 equivalent concentration is a measure of radiative forcing (RF). However, two alternative kinds of CO_2 equivalent concentration are in use, respectively based on RF from GHGs only (CO_2eqGHG) and on total RF (CO_2eqTot). The EU 2 degree target is associated with CO_2eqTot, not CO_2eqGHG. These two quantities are significantly different: in 2010, CO_2eqGHG was 445 ppm (nearly 60 ppm higher than the CO_2 concentration of 387 ppm), while CO_2eqTot was about the same as the CO_2 concentration itself, because of near-cancellation between the present warming RF from non-CO_2 GHGs and cooling (negative) RF from non-gaseous agents including aerosols. The cooling RF from aerosols is likely to diminish in future and the near-cancellation is unlikely to continue, leading to additional net warming.

3. Future radiative forcing (and thence global temperature) depends on future scenarios for GHG emissions and thence GHG concentrations, as well as RF from non-gaseous agents including aerosols. Recently, four Representative Concentration Pathways have been developed to provide the primary scenarios for all these forcing agents to be used in the IPCC Fifth Assessment Report (AR5) due in 2013. The RCP approach is fundamentally different from that of the SRES scenarios used in AR4 (2007), because it starts from concentrations, not emissions. Noteworthy features of the RCP scenarios are:

- Three of the four RCPs span the range of forcings covered by the earlier SRES scenarios, but the fourth is a low-forcing "peak and decline" scenario outside the SRES range.
- In all RCP scenarios, the negative RF from non-GHG forcing (mainly from aerosols) declines rapidly from 2000 onward, unlike the RF from GHGs. This implies a decrease in the cooling effect

from non-GHG forcing. The peak in negative forcing around 2000 is very strong in all scenarios, implying rapid postulated improvements in air quality.

4. Recent work (Allen *et al.* 2009, Meinshausen *et al.* 2009; Matthews *et al.* 2009; Zickfeld *et al.* 2009; Raupach *et al.* 2011) has linked *cumulative* CO_2 emissions (Q) directly to warming (ΔT) without passing explicitly through the intermediate steps of concentrations and radiative forcing. As a result, there is developing policy interest in the concept of "carbon budgets", or allowable quotas for emissions of CO_2 and other GHGs for a long period into the future. The cumulative quota or budget approach includes uncertainty (comparable with uncertainties in other approaches and other aspects of climate science) but also provides a simple, minimally ambiguous link between potential policy commitments and warming outcomes, while allowing considerable flexibility in implementation detail. The reason that it works is that up to just before peak warming, temperature trajectories collapse approximately to a common curve when time is measured with a "cumulative-emission clock".

5. The cumulative-emission concept has so far been developed for CO_2. The science needed to link cumulative emissions of multiple gases warming is still under development, but here we provide *highly preliminary* calculations of cumulative GHG emission quotas for multiple GHGs, in terms of CO_2 equivalent emissions from long-term global warming potentials. *These estimates are the best available at present but may change with further work.*

6. A simple measure of the cumulative emission quota is provided by the "quota time scale", the ratio (Q_m/F_m) of the available cumulative emission at the mitigation start time (Q_m) to the initial emission at that time (F_m). This is the time for which emissions can continue at their starting rate before the quota is exhausted. Considering the climate change effects of CO_2 only, the cumulative emission quota to stay below 2 degrees of warming with 50% probability is about 1000 GtC[1] from 1750, or 460 GtC from 2010 (because about 540 GtC has been emitted between 1750 and 2010). The corresponding quota time scale Q_m/F_m is 50 years. Considering the climate change effects of all GHGs, quota time scales are shorter than for CO_2 only. The required global decarbonisation rate is over 5% per year in the long-term exponential-decline phase of mitigation. This exceeds almost all historically observed national or regional rates of decarbonisation, but these examples have always involved decarbonisation as a side effect of some other event or process, not an intentional policy goal.

7. Increasing the required probability of success in meeting the temperature target has a major effect on concentration and emission goals to meet given warming targets. In broad terms, increasing the required probability of success from 50% to 80% is equivalent to lowering the temperature target by about 0.7 degrees. In terms of the available cumulative emissions to meet a warming target of 2 degrees, the same increase (50% to 80% probability of success) reduces the cumulative GHG budget by a factor of 4, from 440 to 105 GtCeqEmis (Table S1), and decreases the quota time scale from 37 years to an impossible 9 years. The combination of a 2 degree warming target with high probability of success is now unreachable.

8. There has been limited progress toward climate goals from recent national commitments associated with the 2009 Copenhagen Accord, which invited Annex 1 Parties (developed countries) to submit emission reduction targets for 2020 and non-Annex 1 Parties (emerging economies and developing countries) to commit to mitigation actions.

- The non-Annex-1 share of global emissions is expected to grow quickly: it is estimated as about 2/3 in 2020, compared with only 1/3 in 1990.

[1] In this report, cumulative CO_2 emissions are expressed mainly in GtC or Gigatonnes of carbon; 1 GtC = 10^9 tonnes of carbon = 1 billion tonnes of carbon. Cumulative emissions in units of CO_2 mass (say $GtCO_2$) are equal to 44/12 = 3.67 times cumulative emissions in units of carbon mass, because a CO_2 molecule contains 2 oxygen atoms and has a mass 44/12 times the mass of its single carbon atom.

- Many Annex 1 countries have provided two mitigation targets, a lower target as an unconditional commitment and a higher target associated with higher global ambition reflected in stronger commitments by other countries.
- The "mitigation actions" currently promised from many non-Annex-1 countries are expressed in terms of efficiency improvements rather than absolute emissions, and require assumptions to translate them into actual emission reductions or emissions avoided.
- Having Annex 1 countries adopt higher rather than lower targets would reduce emissions by about 4-6% of business-as-usual (BAU) emissions by 2020. There would also be additional emission reductions by 2020 of 2-4% of BAU emissions if countries were to move from lenient rules to strict ones. The adoption of strict rules would also solve some key uncertainties including the carry-over of underspent emissions allowances in the Kyoto Protocol into the new targets (particularly by Eastern European countries).
- Two issues remain unresolved: (a) the potential for double counting of emissions offsets, where both the provider and the buyer count them as part of their targets; and (b) the development of baselines or BAU scenarios, for which the underlying details are often not specified –a tendency to make BAU scenarios high (so that apparent emission avoidance can be larger) may lead to an additional 1.5 $GtCO_2eqGHG\ y^{-1}$ by 2020.

9. The most important aspect of 2020 targets is not the emissions reductions themselves (which are likely to be modest, both nationally and globally) but the extent to which they embed long-term decarbonisation strategies. The challenge can be expressed in terms of a cumulative emissions quota, a mitigation time scale, a long-term mitigation rate, or a reduction target for 2050. All of these metrics can be related to each other (Table S1). The long-term challenge is already severe, and failure to meet modest 2020 targets will make it unachievable.

Table S1 Conversion table for climate goals, from the spread sheet accompanying this report See Appendix D for details.

Goal: Temperature rise above preindustrial	Probability of meeting goal	CO2 equivalent concentration	CO2 equivalent concentration	APPROX CO2 equivalent concentration	Carbon budget or quota (2010 onward)	Carbon budget or quota (2010 onward)	Quota time scale (time to spend carbon budget at 2010 rate)	APPROX GHG budget or quota (2010 onward)	APPROX GHG budget or quota (2010 onward)	Quota time scale (time to spend GHG budget at 2010 rate)
		Total from all agents	All GHGs (excl O3)	Contribution from CO2 only	CO2 only world	CO2 only world	CO2 only world	All GHGs (excl O3)	All GHGs (excl O3)	All GHGs (excl O3)
degrees C	percent	ppm CO2eqTot	ppm CO2eqGHG	ppm CO2	GtC	GtCO2	years from 2010	GtCeqEmis	GtCO2eqEmis	years from 2010
1	**50**	353	373	342	-76	-280	-8	-111	-406	-9
1.5	50	396	419	371	183	669	19	156	573	13
2	**50**	**444**	**470**	**402**	**458**	**1679**	**47**	**440**	**1612**	**37**
3	50	560	592	473	1057	3874	109	1053	3862	88
4	50	706	746	556	1716	6293	177	1727	6334	144
1	**67**	339	359	333	-160	-585	-16	-197	-722	-16
1.5	67	374	395	356	50	182	5	19	71	2
2	**67**	**411**	**435**	**381**	**271**	**993**	**28**	**247**	**905**	**21**
3	67	498	527	436	746	2737	77	736	2697	61
4	67	604	639	499	1265	4640	131	1267	4645	106
1	**80**	329	348	326	-222	-814	-23	-261	-959	-22
1.5	80	357	378	345	-49	-180	-5	-83	-303	-7
2	**80**	**387**	**410**	**366**	**132**	**485**	**14**	**105**	**383**	**9**
3	80	456	482	410	520	1906	54	503	1844	42
4	80	536	567	459	939	3442	97	933	3419	78

Table S2 Properties of cumulative carbon budgets, from the spread sheet accompanying this report. See Appendix D for details.

Year in which mitigation is started	Allocated carbon budget (CO2 only world) (1750 onward)	Allocated carbon budget (CO2 only world) (2010 onward)	Allocated carbon budget (CO2 only world) (1750 onward)	Allocated carbon budget (CO2 only world) (2010 onward)	Median warming above preindustrial (CO2 only world)	Year of peak emissions	Emissions decline rate after peak (exponential decay of emissions)	Emission in year 2020	Emission in year 2050
year	GtC	GtC	GtCO2	GtCO2	degrees C	year	% per year	Percent of 1990 emission	Percent of 1990 emission
2011	**1000**	458	3667	1679	2.00	2017	5.64	144	65
2015	1000	458	3667	1679	2.00	2020	6.78	161	63
2020	1000	458	3667	1679	2.00	2023	8.87	177	56
2025	1000	458	3667	1679	2.00	2027	12.41	177	45
2011	**1500**	958	5500	3513	2.84	2027	3.12	158	135
2015	1500	958	5500	3513	2.84	2028	3.54	169	145
2020	1500	958	5500	3513	2.84	2030	4.20	177	158
2025	1500	958	5500	3513	2.84	2032	5.08	177	174
2011	**2000**	1458	7333	5346	3.62	2036	2.28	162	170
2015	2000	1458	7333	5346	3.62	2036	2.55	171	184
2020	2000	1458	7333	5346	3.62	2037	2.94	177	204
2025	2000	1458	7333	5346	3.62	2039	3.43	177	227
2011	**2500**	1958	9167	7179	4.35	2044	1.85	164	189
2015	2500	1958	9167	7179	4.35	2044	2.05	172	206
2020	2500	1958	9167	7179	4.35	2044	2.33	177	228
2025	2500	1958	9167	7179	4.35	2045	2.67	177	255
2011	**3000**	2458	11000	9013	5.03	2052	1.59	165	203
2015	3000	2458	11000	9013	5.03	2051	1.74	173	220
2020	3000	2458	11000	9013	5.03	2051	1.97	177	244
2025	3000	2458	11000	9013	5.03	2051	2.23	177	271

Table S3 Properties of cumulative greenhouse gas budgets, from the spread sheet accompanying this report. See Appendix D for details.

Year in which mitigation is started	Allocated GHG budget (all GHGs excl O3) (1750 onward)	Allocated GHG budget (all GHGs excl O3) (2010 onward)	Allocated GHG budget (all GHGs excl O3) (1750 onward)	Allocated GHG budget (all GHGs excl O3) (2010 onward)	Median warming above preindustrial (without aerosol cooling)	Median warming above preindustrial (including aerosol cooling)	Year of peak emissions	Emissions decline rate after peak (exponential decay of emissions)	Emission in year **2020**	Emission in year **2050**
year	GtCeqEmis	GtCeqEmis	GtCO2eqEmis	GtCO2eqEmis	degrees C	degrees C	year	% per year	Percent of 1990 emission	Percent of 1990 emission
2011	**1140**	440	4180	1613	2.24	2.00	2015	7.02	137	43
2015	1140	440	4180	1613	2.24	2.00	2018	8.71	156	37
2020	1140	440	4180	1613	2.24	2.00	2022	12.13	177	26
2025	1140	440	4180	1613	2.24	2.00	2026	19.09	177	11
2011	**1500**	800	5500	2933	2.84	2.60	2021	4.25	152	99
2015	1500	800	5500	2933	2.84	2.60	2023	4.94	166	102
2020	1500	800	5500	2933	2.84	2.60	2025	6.11	177	106
2025	1500	800	5500	2933	2.84	2.60	2029	7.83	177	108
2011	**2000**	1300	7333	4767	3.62	3.38	2028	2.91	159	143
2015	2000	1300	7333	4767	3.62	3.38	2030	3.29	170	154
2020	2000	1300	7333	4767	3.62	3.38	2031	3.87	177	169
2025	2000	1300	7333	4767	3.62	3.38	2033	4.64	177	187
2011	**2500**	1800	9167	6600	4.35	4.10	2036	2.29	162	169
2015	2500	1800	9167	6600	4.35	4.10	2036	2.55	171	183
2020	2500	1800	9167	6600	4.35	4.10	2037	2.95	177	203
2025	2500	1800	9167	6600	4.35	4.10	2039	3.44	177	227
2011	**3000**	2300	11000	8433	5.03	4.79	2043	1.92	164	186
2015	3000	2300	11000	8433	5.03	4.79	2043	2.13	172	202
2020	3000	2300	11000	8433	5.03	4.79	2043	2.43	177	224
2025	3000	2300	11000	8433	5.03	4.79	2044	2.79	177	250

1 INTRODUCTION

A simple view of human-induced climate change consists of a causal chain with just four links: (1) anthropogenic emissions of greenhouse gases lead to (2) rising atmospheric greenhouse gas concentrations, leading to (3) climate change (global warming, changed weather patterns, melting ice and other physical and chemical changes), leading to (4) impacts of climate on human societies and natural ecosystems. An initial driver over which humans have control (emissions) leads through intermediate responses (concentrations, temperatures and other climate changes) to a final response (climate impacts). To set goals for limiting climate change to acceptable levels, the basic principle is to work backwards through the causal chain. The first requirement is a quantification of "dangerous anthropogenic interference with the climate system" (UNFCCC 1992). This determines a threshold beyond which climate impacts are unacceptable, from which science can infer the associated threshold for physical climate change, then the corresponding greenhouse gas concentration threshold, and finally the emissions targets needed to keep the risk of "dangerous" outcomes below "unacceptable" levels (quotes denote value judgements).

Life is not so simple in practice. The first complication is *connectivity*: the real world is much more complex than a linear causal chain (PMSEIC 2010). Climate and human societies exist in a network of myriad interconnections, so actions at one point (for example, policies to reduce emissions or a decision not to reduce emissions) create ripple effects with consequences far broader than the intended outcome of the action along the linear chain. A second complication is *uncertainty* (IPCC 2007a; AAS 2010). Broadly speaking, uncertainty increases along the forward chain: predicting concentrations from an emission scenario (stepping from link 1 to 2) involves less uncertainty than predicting climate from concentrations (2 to 3), while predicting climate impacts on economies and ecosystems (3 to 4) is the most uncertain step of all. There is a corresponding amplification of uncertainty in moving backwards through the chain to set emissions targets. The third and most difficult complication is *subjectivity.* Essential value judgements are required for setting climate goals, to decide what climate impacts are "dangerous", and what levels of risk are "acceptable".

The complications of connectivity, uncertainty and subjectivity are widely recognised, though often not made explicit. Largely because of them, there exists a plethora of global goals for "avoiding dangerous anthropogenic interference with the climate system" (UNFCCC 1992). These are of four broad types:

- Temperature targets, such as limiting global warming to two degrees Centigrade above preindustrial temperatures, the European Union target set in 1996 (European Commission 2008) and recently adopted by the Copenhagen Accord (UNFCCC 2009);
- Concentration targets, such as keeping greenhouse gas concentrations below 450 ppm CO_2eq;
- Year-based emission targets, such as a five per cent or twenty per cent reduction in 1990 or 2000 emissions by 2020, or a 60 per cent reduction by 2050;
- Cumulative-emission or "carbon budget" targets, which require long-term cumulative emissions (from a nominated start time such as 1750 or 2000) to be less than a set quota.

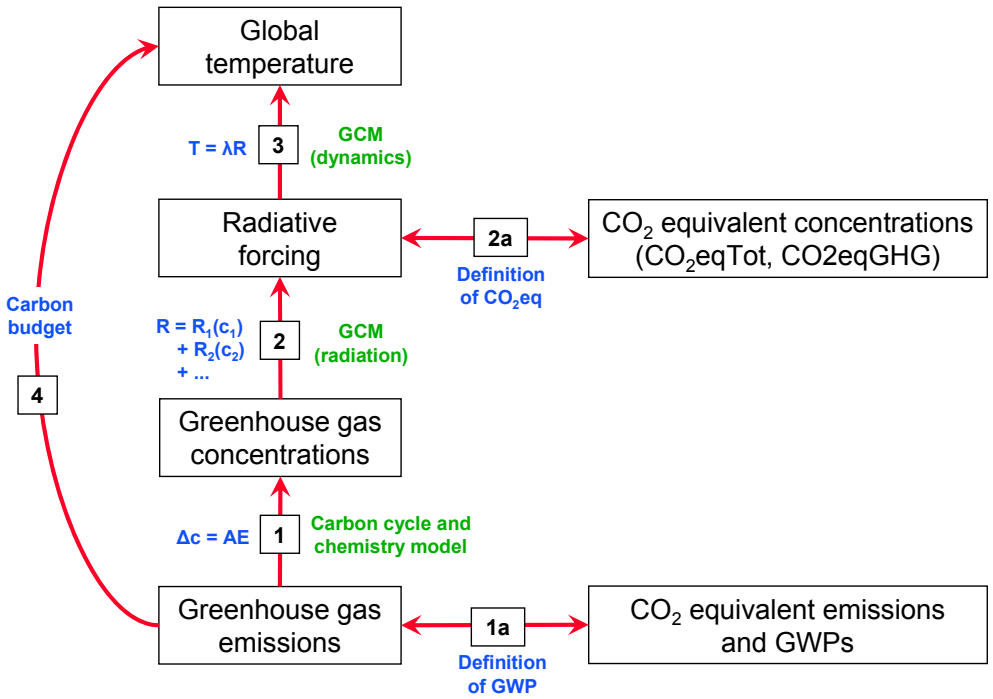


Fig. 1 Architecture of relationships between GHG emissions, GHG concentrations, and global temperature. Blue labels indicate simplified models for links between elements, green labels indicate more complex models. Symbols are defined later in the text. Note the different roles of CO_2 equivalent concentration (a measure of radiative forcing) and CO_2 equivalent emissions (a means of bring emissions of different entities to a common basis).

The purpose of this report is to relate these different statements of climate goal. Figure 1 provides an architecture for the links between GHG emissions, GHG concentrations and global temperature to be traced in this report. The links can be made quantitative with models ranging from simple equations through to complex numerical codes such as Global Climate Models (GCMs). These are respectively indicated in Fig. 1 in blue and green text.

In this report we will describe the links in Fig. 1 broadly in reverse causal order, following the principle stated at the outset. Section 2 reviews the concept of "dangerous human interference with the climate system". Section 3 discusses two aggregate measures, radiative forcing and climate sensitivity, which establish links 3, 2 and 2a. Section 4 describes the links between greenhouse gas emissions and concentrations and thence to radiative forcing, establishing links 1 and 1a. Section 5 outlines the "carbon budget" or cumulative-emission concept supporting link 4, and analyses the constraints on global emissions trajectories required to achieve a given temperature target - for example, how the year of peak emissions and the necessary subsequent rate of decline relate to a given cumulative quota. Section 6 addresses two further issues: first, we explore how climate goals are influenced by uncertainty in the science of climate change. In other words, how can climate goals be stated in the language of probability and risk? Second, we compare the global climate goals with likely global emissions in 2020 from present trajectories and national commitments under the Copenhagen Accord (2009).

2 DEFINING "DANGEROUS HUMAN INTERFERENCE WITH THE CLIMATE SYSTEM"

This section reviews attempts to quantify "dangerous human interference with the climate system", the goal of the UN Framework Convention on Climate Change (UNFCCC 1992). Much recent work has been given to this question (for example Schellnhuber *et al.* 2006; Schneider and Lane 2006; Smith *et al.* 2009). A basic problem that the drivers of climate change are globally shared (the atmosphere mixes all anthropogenic emissions) whereas impacts are regional. Some may benefit from aspects of climate change, while many more will lose.

The global sharing of emissions through atmospheric mixing makes a global climate goal essential, although the consequences of this goal will be experienced very differently in different regions. The most prominent global goal expressed to date is limiting global warming to 2 degrees Centigrade above preindustrial temperatures, the European Union (EU) target set in 1996 (European Commission 2008) and adopted by the 2009 Copenhagen Accord (UNFCCC 2009).

This target has been subject to several kinds of criticism. First, some scientists (prominently Hansen *et al.* 2008 and elsewhere) have argued that 2 degrees is too high, and that avoiding "dangerous" climate change requires a lower target of 1.5 or 1 degree. Two foundations for this position (among others) are (a) there is a risk of crossing thresholds or tipping points in the climate system, which are hard to predict but would cause rapid global climate change if they were to occur (Kriegler *et al.* 2009; ACERE-NSF 2009); and (b) a high equilibrium sensitivity of sea level to natural climate change (around 15-20 metres per degree of warming) can be inferred from records of glacial cycles through the last million years (e.g. Hansen *et al.* 2008). There is increasing concern that sea levels can respond to warming in sudden jumps as land ice sheets are destabilised (e.g. Rignot *et al.* 2008a; Rignot *et al.* 2008b; Hansen *et al.* 2008).

The second criticism of the EU target is opposite, that it is too low. This is implicit in arguments that humanity can adapt to significant levels of climate change, and that the mitigation cost of 2 degree target would be prohibitive. However, there is an emerging consensus in the economic literature that a 2 degree target would provide net economic benefits (Smith 2011).

Third, a 2 degree target is criticised as too blunt, without the ability to deal adequately with risks of regional climate impacts or thresholds (e.g. Lenton 2011), or to identify anthropogenic climate change impacts which are not directly temperature-related, such as ocean acidification.

Given these issues and tensions, a useful view of the 2 degree global temperature target is that it is a social construct (N. Nakicenovic, personal communication), similar to many hard numeric limits in law and regulation that are designed to limit risks to society and individuals. Examples include maximum pollution levels, speed limits, and age limits for drinking, driving or sexual consent. The legislated hard thresholds at which the associated risks become "unacceptable" are broad-brush societal rules designed to limit risks which are actually quite situation-dependent. They are based on ethical and social considerations as well as scientific risk assessment.

With all of this in mind, we use two degrees as a sample global temperature target, and also consider other targets (both higher and lower) through tables, graphs and discussion.

3 CLIMATE AND RADIATIVE FORCING

3.1 Overview

The climate and temperature of the Earth are largely controlled by greenhouse gases (GHGs) in the atmosphere, which interact with radiation and thereby affect the global energy balance. Human-induced forcing on climate arises mainly from anthropogenic emissions of GHGs, principally carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons[2]. Ozone, another significant GHG, is a highly reactive gas that is formed and destroyed by chemical reactions in the atmosphere rather than by direct anthropogenic emission. Aerosols (minute particles or droplets floating in the atmosphere) also interact with radiation, both reflecting solar radiation (light) and absorbing and reradiating heat, thereby contributing to climate forcing.

Other influences on the Earth's energy balance and temperature arise through feedbacks rather than forcings (AAS 2010). Water vapour is an important GHG but it largely responds to temperature through an amplifying feedback, rather than controlling it (Schmidt *et al.* 2010; Sherwood *et al.* 2010a; Sherwood *et al.* 2010b). A second important feedback arises through changes in the albedo (brightness) of the Earth's surface primarily through darkening (decreases in albedo) as polar ice caps melt in response to warming (Hansen *et al.* 2008). A third important class of feedbacks arise through the natural carbon cycle (Friedlingstein *et al.* 2006).

To quantify anthropogenic influences on climate in the manner needed here, two basic elements are required: an aggregate measure of the anthropogenic *forcing* on the climate system, and an aggregate measure of the climate *response* to forcing, including the effects of feedbacks. The first is quantified by radiative forcing, and the second is climate sensitivity.

3.2 Radiative forcing

3.2.1 Definition

The net input of energy to the earth is measured by the net radiative forcing, the downward flux of radiant energy at the top of the troposphere under specified conditions[3]. When positive as at present, this energy input causes a net warming of the atmosphere and oceans.

Contributions to net radiative forcing are shown in Fig. 2. They can be grouped into contributions from three kinds of agent:

[2] GHGs are often grouped into Kyoto gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) and Montreal gases (CFCs, HCFCs, CH_3CCl_3). Ozone (O_3) is formed and destroyed chemically in the atmosphere, with its destruction being aided catalytically by Montreal gases. Kyoto and Montreal GHGs are often collectively referred to as long-lived GHGs.

[3] The IPCC definition of radiative forcing (IPCC 2001, Section 6.1.1) is: "the radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent (say, a change in greenhouse gas concentrations) is the change in net (down minus up) irradiance (solar plus long-wave; in Wm^{-2}) at the tropopause AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values". The tropopause is the top of the troposphere, the well-mixed part of the atmosphere with a typical depth of 10-15 km.

- CO_2 contributes about +1.7 W m^{-2} (Watts per square metre);
- Other long-lived (Kyoto and Montreal) GHGs (methane, nitrous oxide, halocarbons) contribute about +1.0 W m^{-2};
- Other agents (aerosols, ozone, albedo etc.) together contribute a negative (cooling) radiative forcing of about −1.0 W m^{-2}. The largest contribution in this group comes from aerosols. There is large uncertainty in the radiative forcing from aerosols because of the processes involved are complex, as outlined below.

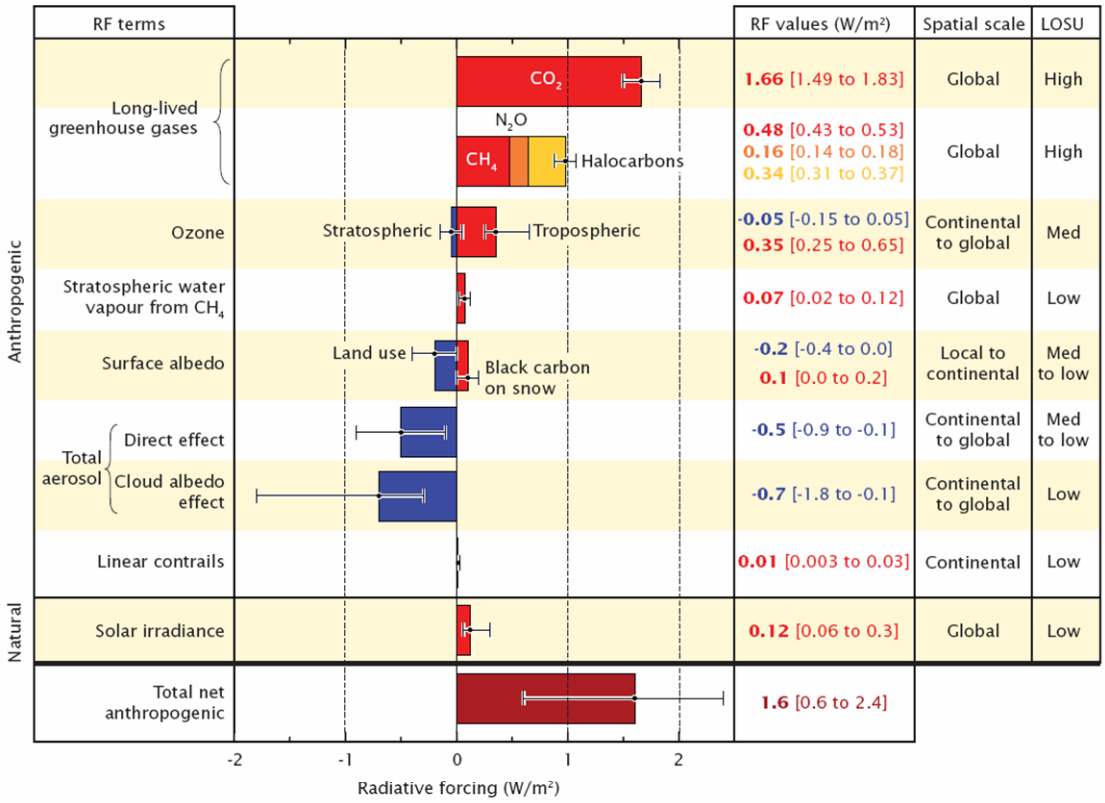


Fig. 2 Components of radiative forcing (RF), their 90% confidence intervals, their geographic extent, and their level of scientific understanding (LOSU) in 2005 (Figure 2.4 in IPCC 2007a, Figure 2.20 in IPCC 2007b). The total net human-induced radiative forcing (1.6 W/m^2) is not a simple sum of the components (see text).

The combination of all these contributions gives a positive net radiative forcing of +1.6 W m^{-2} in 2005, with 90% confidence interval 0.6 to 2.4 W/m^2. This is similar to the radiative forcing from CO_2 alone, because at present the contributions from other long-lived GHGs and other agents (aerosols, ozone etc.) approximately cancel. This situation is unlikely to continue in future because a probable future decrease in pollution-based aerosols in the atmosphere will reduce their negative (cooling) contribution to radiative forcing, resulting in increased warming (see below).

Net radiative forcing is a globally aggregated measure of processes that have different distributions in space and time. Some forcing agents, such as long-lived GHGs, are fairly well mixed through the global atmosphere. The radiative forcing contributions from these processes can be approximately summed to give their total contribution to net radiative forcing. Other forcing agents, such as aerosols, have strong regional variations and affect climate in more complex ways (see below). Individual contributions from these agents do not combine into the global net radiative forcing through simple summation. For this reason as well as others (IPCC

2001, Section 6.1 and 6.2; IPCC 2007b, Section 2.2) the net radiative forcing of +1.6 W/m^2 is not a simple sum of the contributions in Fig. 2. Similarly, uncertainties cannot be combined in simple root-mean-square fashion.

Taking these factors into account, we can write the total radiative forcing (RF) as

$$\mathrm{RF} = \mathrm{RF}_{\mathrm{CO2}} + \underbrace{\mathrm{RF}_{\mathrm{nonCO2GHGs}}}_{\substack{\mathrm{CH4,\ N2O,}\\ \mathrm{halocarbons}}} \underset{\mathrm{approx}}{+} \underbrace{\mathrm{RF}_{\mathrm{Other}}}_{\substack{\mathrm{Aerosols,\ ozone,}\\ \mathrm{albedo\ etc.}}} \qquad (1)$$

where the first term on the right is the contribution from CO_2, the second is the contribution from long-lived non-CO_2 gases (excluding ozone, a very short-lived gas), and the third is the contribution from other agents, with aerosols being the most important in this group. The "approx." under the last plus sign is a reminder that the contributions from this last group do not sum in linear fashion into the total radiative forcing. In contrast, the contributions from CO_2 and other gases) can be approximately summed.

3.2.2 Radiative forcing by GHGs

The radiative forcing from an anthropogenic greenhouse gas is a function of its concentration:

$$\text{Radiative forcing from gas } n \left[\mathrm{W\ m^{-2}} \right] = \mathrm{RF}_n \left(c_n \right) \qquad (2)$$

where c_n is the concentration of gas n (CO_2, CH_4, N_2O, halocarbons, ...). In some cases there are small interaction terms, meaning that the radiative forcing for one gas depends not only on its concentration but on the concentration of another gas as well; the most important interaction is between CH_4 and N_2O. The units of RF are W m^{-2}, and the units of concentration are whatever is convenient for the gas, usually ppm (parts per million) for CO_2 and ppb (parts per billion) for other gases. Figure 3 shows the relationships between radiative forcing and concentration for several major GHGs (derived from expressions given in IPCC 2001 p358).

The relationships in Fig. 3 are linear for gases at low concentrations, such as synthetic gases, but are nonlinear for gases at higher concentrations such as CO_2, CH_4 and N_2O. For these gases, each additional unit of concentration causes a slightly smaller increment in radiative forcing, because of progressive saturation of the infrared spectral lines responsible for energy exchanges between gas molecules and heat radiation. Saturation effects are measured by the sensitivity of radiative forcing to concentration, also called the radiative efficiency. This quantity is shown in Fig. 4. It decreases with increasing concentration when saturation effects are occurring.

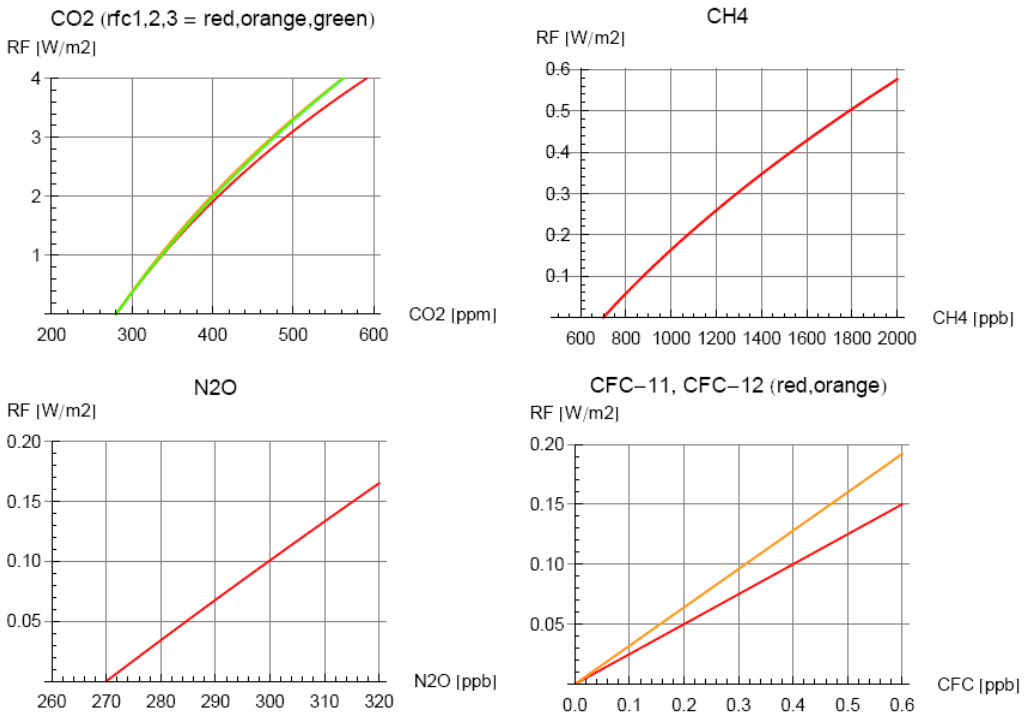


Fig. 3 Radiative forcing (RF) as a function of gas concentration, for CO_2, CH_4, N_2O and CFCs (IPCC 2001 p358). Of three alternative expressions for RF for CO_2; the first (red) is used here.

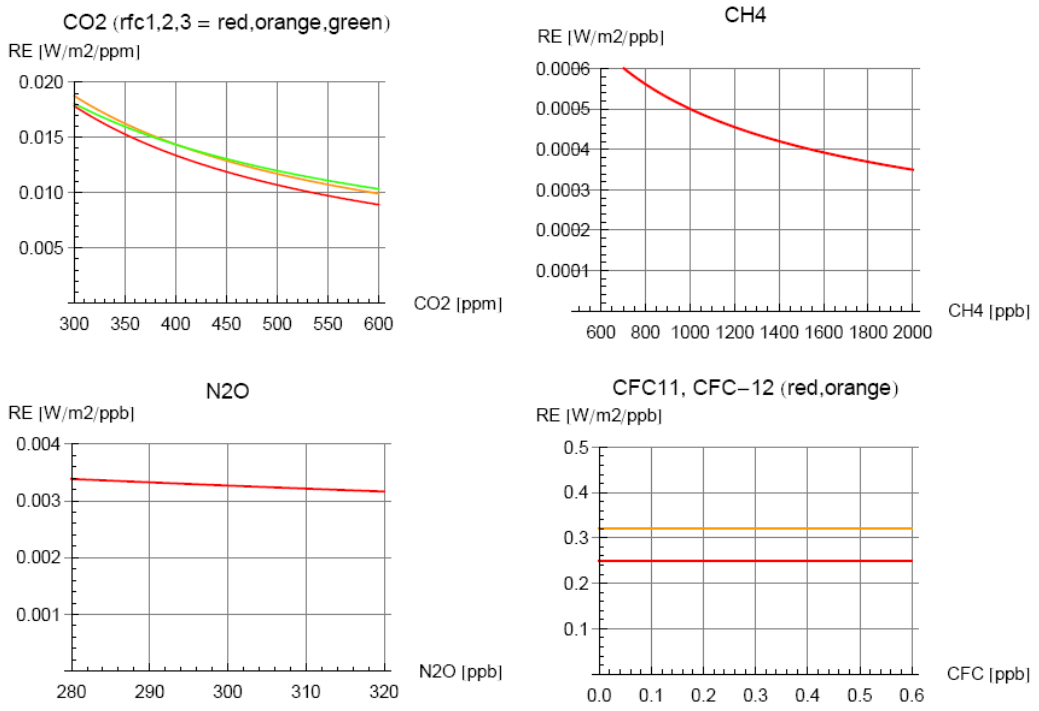


Fig. 4 Radiative efficiency, RE = d(RF)/d(conc), as a function of gas concentration, for CO_2, CH_4, N_2O and CFCs. Details as for Fig. 3.

3.2.3 Radiative forcing by aerosols

Aerosols are small solid particles or liquid droplets in the atmosphere with both natural sources (such as dust, or products of reactions involving naturally occurring biogenic gases such as isoprenes from vegetation) and anthropogenic sources (such as smoke particles). As indicated above, they exert significant radiative forcing which in aggregate is negative (cooling) at present. The radiative forcing effects of aerosols are complex and often not adequately included in discussions of climate goals. Therefore, we offer here a short review of forcing by aerosols.

There are three principal ways in which aerosols affect the Earth's climate. First, aerosol particles alter the radiative characteristics of the atmosphere by absorbing, emitting and reflecting radiation. This directly alters the radiation received at the surface and hence surface temperatures. Second, many aerosol particles can act as cloud condensation nuclei for both liquid water and ice droplets, thereby affecting cloud properties and the hydrological cycle (either directly or through atmospheric dynamics). For example, rainfall variability in north-western Australia has been linked to aerosol loading (Rotstayn *et al.* 2009; Rotstayn *et al.* 2010). Third, interactions between radiation, clouds and the global circulation patterns can result in further indirect effects; for example, radiation absorbed by aerosols can warm cloud layers, thereby promoting cloud dissipation as the local relative humidity decreases (Koch and Del Genio 2010).

Aerosols generally have short (1-10 day) residence times, implying that the impacts of aerosols are more closely tied to their sources, both in time and space, than those of long-lived GHGs. However, large-scale impacts are also observed (Ramanathan and Carmichael 2008). The impacts are also contingent on location of the aerosols (height and position), weather conditions (whether there are clouds or not) and the precise make up of the aerosol mix. As a result of these myriad, often competing and nonlinear, effects and the inherent difficulties in measuring these microscopic particles and their impacts, the general level of scientific understanding of the role of aerosols in the climate system remains low (IPCC 2007b, Chapter 2).

Estimates for the current (2005) radiative forcing of the Earth's climate are as follows (all from IPCC 2007b, Figs. 2.20, 2.21, Table 2.12). Contributions due to anthropogenic aerosols are −0.5 (range −0.9 to −0.1) W m^{-2} for the direct radiative effect and −0.7 W m^{-2} (range −1.8 to −0.3) for the indirect (cloud) effects (ranges are 90% confidence intervals; that is, there is a 90% chance that the true value lies within this band). For comparison the forcing due to all long-lived GHGs is estimated (IPCC 2007b) as 2.63 W m^{-2} (range 2.37 to 2.89) The estimated forcing due to persistent aircraft contrails (linked to aerosols) is +0.01 W m^{-2} (range 0.003 to 0.03). The forcing due to black carbon aerosol on snow (enhanced snow ageing) is estimated at +0.1 W m^{-2} globally (range 0 to 0.2) with much larger local regional values including remote areas (Koch and Hansen 2005). The combined radiative forcing due to aerosols is comparable to that due to non-CO_2 GHGs, but much more uncertain.

Recent discussions around climate mitigation have included some around measures to reduce the anthropogenic emissions of one specific type of aerosol – black carbon (Baron *et al.* 2009; Kandlikar *et al.* 2009). Anthropogenic emissions of black carbon, primarily from the incomplete combustion of diesel fuel, have been estimated to warm the climate by 0.2 W m^{-2} (range 0.05 to 0.35) directly and contribute significantly to enhanced snow ageing (IPCC 2007b, Table 2.12). Policy measures designed to reduce emissions of black carbon are expected to improve energy efficiency and significantly improve near-surface air quality (with its associated beneficial health impacts) as well as decreasing global radiative forcing. However, aerosols are rarely emitted in isolation of each other. Attempts to clean up emissions of black carbon may also lead

to reductions in the emissions of other (cooling) aerosols and hence lead to increased global warming (Arneth *et al.* 2009; Brasseur and Roeckner 2005).

In summary, most scenarios anticipate a decrease in the net cooling effect from aerosols (discussed further in Section 4.2). This has the potential to make stabilisation targets more difficult to achieve (Ramanathan and Feng 2008).

3.2.4 CO_2 equivalent concentration as a measure of radiative forcing

In economic and policy analyses of climate change (for instance Stern 2006; Garnaut 2008) it is common to refer to radiative forcing not in W m^{-2} as above, but as a "CO_2 equivalent concentration". This is the concentration of CO_2 that would give the same radiative forcing as the actual mix of greenhouse gases and other forcing agents present in the atmosphere (including direct forcings only). It is defined so that:

$$\mathrm{RF} = 5.35 \ln\left(\frac{\mathrm{CO_2eq}}{280}\right); \qquad \mathrm{CO_2eq} = 280 \exp\left(\frac{\mathrm{RF}}{5.35}\right) \tag{3}$$

with RF in W m^{-2} and CO_2 in ppm. This comes from the first and simplest of three alternative expressions for the radiative forcing by CO_2 (IPCC 2001 p358)[4].

Figure 5 shows the relationship between RF and CO_2eq, which is logarithmic rather than linear because of the saturation effect mentioned above. Because RF is measured relative to a pre-industrial climate assumed to be in equilibrium, the RF is zero at the assumed preindustrial CO_2eq concentration of 280 ppm.

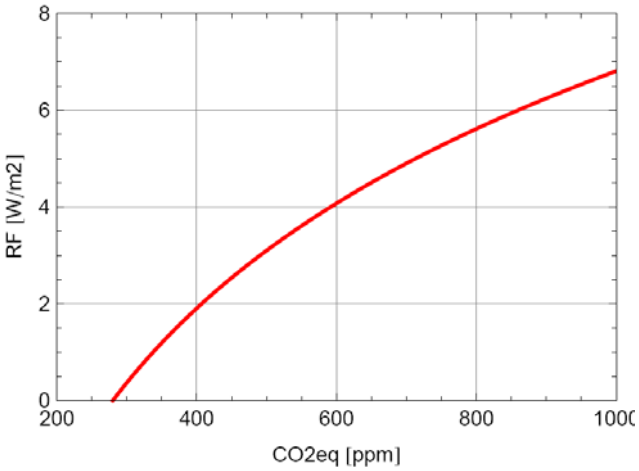


Fig. 5 The relationship RF = 5.35 ln(CO_2eq/280).

The CO_2 equivalent concentration is uniquely related to radiative forcing by Equation (3). However, two alternative kinds of CO_2 equivalent concentration are in use, respectively based on RF from long-lived GHGs only and on total RF. This important distinction can be clarified by writing (similar to Equation (1)):

[4] The numerical constants in Equation (3) are widely used. Recent calculations of CO_2eq for Representative Concentration Pathways (RCPs) have used slightly different coefficients: RF = 5.3524 ln(CO_2eq/278). (See http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about)

$$\mathrm{RF_{Tot}} = \underbrace{\mathrm{RF_{GHG}}}_{\substack{\mathrm{CO2,\ CH4,\ N2O,}\\ \text{halocarbons}}} \underset{\text{approx}}{+} \underbrace{\mathrm{RF_{Other}}}_{\substack{\text{Aerosols, ozone,}\\ \text{albedo etc.}}} \qquad (4)$$

This is a simplification of Equation (1) in which all GHG contributions from CO_2 and other GHGs are lumped together as RF_{GHG}. Applying the definition of CO_2eq separately to RF_{GHG} and RF_{Tot}, we obtain two CO_2 equivalent concentrations:

$$\mathrm{CO_2eqGHG} = 280 \exp\left(\frac{\mathrm{RF_{GHG}}}{5.35}\right); \qquad \mathrm{CO_2eqTot} = 280 \exp\left(\frac{\mathrm{RF_{Tot}}}{5.35}\right) \qquad (5)$$

These will be denoted throughout this report as CO_2eqGHG and CO_2eqTot, respectively, because they are significantly different and are not usually distinguished. In 2010, CO_2eqGHG was about 445 ppm (nearly 60 ppm higher than the CO_2 concentration of 387 ppm) and CO_2eqTot was about the same as the CO_2 concentration because of the near cancellation at present between the RF from non-CO_2 GHGs and RF from non-gaseous agents including aerosols.

Because RF contributions are (approximately) additive and CO_2eq is exponential in the RF, there is a simple multiplicative relationship between the two CO_2 equivalent concentrations:

$$\mathrm{CO_2eqTot} \approx \exp\left(\frac{\mathrm{RF_{Other}}}{5.35}\right) \times \mathrm{CO_2eqGHG} \qquad (6)$$

For example, taking RF_{Other} as -1.0 W m^{-2}, this yields CO_2eqTot ≈ 0.83 CO_2eqGHG. If RF_{Other} falls to zero in future, then the two CO_2 equivalent concentrations will be equal: CO_2eqTot = CO_2eqGHG.

3.3 Climate response and climate sensitivity

Climate sensitivity defines the response of the climate system to a given radiative forcing. The most common form of climate sensitivity in the literature is the *equilibrium* climate sensitivity, λ_q, defined as the long-term equilibrium warming (ΔT_q) in response to a step change of one unit of radiative forcing, maintained steadily after the step. This means that, for a step change in forcing of R_q W m^{-2}, the warming is

$$\Delta T_q = \lambda_q R_q \qquad (7)$$

where λ_q has the units degC per W m^{-2}, where degC denotes degrees Centigrade. The present best estimate for λ_q is about 0.7 degC per W m^{-2}, with wide uncertainty discussed below.

It is also common to give λ_q in units of degC per CO_2 doubling, where the step change in radiative forcing is assumed to come from an instantaneous doubling of CO_2 concentration (usually from 280 to 560 ppm in experiments with Global Climate Models (GCMs), with the concentration held steady at 560 ppm throughout the model run until a steady temperature is obtained). The conversion between λ_q [degC per W m^{-2}] and $\lambda_q^{\mathrm{dblCO2}}$ [degC per CO_2 doubling] is $\lambda_q^{\mathrm{dblCO2}} = 3.71\lambda_q$, where 3.71 W m^{-2} is the radiative forcing for CO_2 doubling from Equation (3). When the step change in radiative forcing is specified in total CO_2 equivalents and the climate sensitivity in degC per CO_2 doubling, Equation (7) for the long-term equilibrium warming becomes

$$\Delta T_q = \frac{\lambda_q^{\mathrm{dblCO2}}}{\ln(2)} \ln\left(\frac{\mathrm{CO_2eqTot}}{280}\right) \qquad (8)$$

The climate sensitivity is one of the most uncertain parameters in the science of climate change. The current best estimate (IPCC 2007a) is $\lambda_q^{\mathrm{dblCO2}} = 3$ degC per CO_2 doubling (range 2 to 4.5; this is a *likely* range in IPCC terminology, implying a probability of 67-90% that the true value lies within this range). The uncertainty range is large, and skewed on the high side (that is, the top 10% of probable values is further away from the best estimate on the high side than the bottom 10% of probable values on the low side). This high and positively skewed uncertainty arises because climate sensitivity depends strongly on reinforcing feedbacks in the climate system, such as those from water vapour, ice albedo and the carbon cycle mentioned above. The existence of strong positive feedbacks in the climate system is well established from paleoclimatic evidence (for example, Hansen *et al.* 2008), but the nature of positive feedbacks means that uncertainties in the climate sensitivity are large (Roe and Baker 2007). The "long-tailed" probability distribution for climate sensitivity leads to a non-negligible probability of very serious long-term outcomes from anthropogenic climate change.

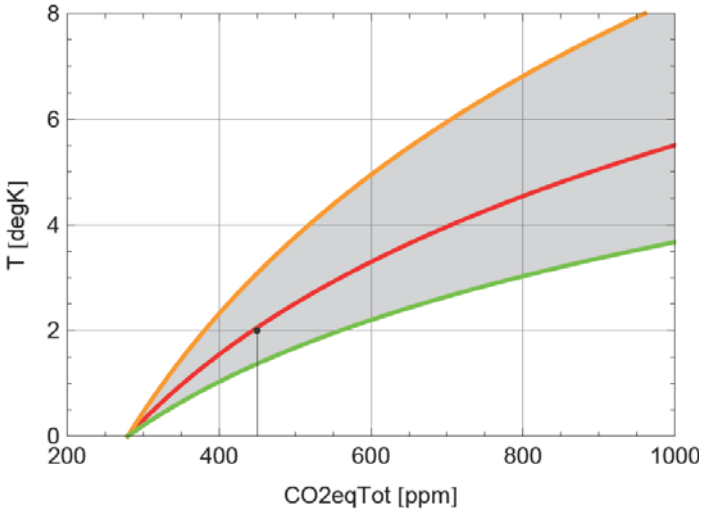


Fig. 6 Warming in response to total radiative forcing specified as CO_2eqTot, for climate sensitivities to CO_2 doubling of 3 (2, 4.5) degC per CO_2 doubling (red, green, orange curves). Curves are from Equation (8). The shaded region is the *likely* warming in IPCC terminology (probability 67-90% of an outcome within this range).

Figure 6 shows the long-term equilibrium warming (ΔT_q) in response to total radiative forcing specified as CO_2eqTot, for climate sensitivities $\lambda_q^{\mathrm{dblCO2}} = 3$ degC per CO_2 doubling (range 2 to 4.5). The shaded region is the *likely* range of outcomes. The point and vertical line indicate the total radiative forcing (as CO_2eqTot) needed to stay below a warming of 2 degrees with 50% probability, CO_2eqTot = 450 ppm, with a *likely* range of values from 380 to 550 ppm.
Figure 6 shows why stabilisation at CO_2eqTot below 450 ppm is associated with keeping warming to less than 2 degrees, the 1996 European Union target for "avoidance of dangerous human interference with the climate system" (European Commission 2008). Note that this target applies to CO_2eqTot, not to CO_2eqGHG, which will be higher; how much higher will depend on the negative radiative forcing from aerosols at stabilisation, as shown by Equation (6).

In the overall architecture of Fig. 1, this section has covered several links. Equations (7) and (8), with Fig. 6, establish links 2a and 3. Equation (2), with Figs. 3 and 4, establishes link 2.

4 GREENHOUSE GAS EMISSIONS AND CONCENTRATIONS

4.1 Overview

In Fig. 1 the first causal connection is link 1, from GHG emissions to GHG concentrations (which then determine radiative forcing through relationships like those in Fig. 3). This link is modelled generically with carbon cycle and atmospheric chemistry models, which calculate the atmospheric concentrations of CO_2, CH_4, N_2O and many other reactive species, with prescribed emissions. The basic principle is to solve the atmospheric mass balances for these entities, accounting for natural and anthropogenic sources and sinks and for chemical reactions.

The mass balance for the atmospheric CO_2 takes the generic form

$$dC_A/dt = F_{\text{Foss}} + F_{\text{LUC}} + F_{BA} + F_{MA} \qquad (9)$$

where C_A is the atmospheric CO_2 store in GtC (related to the atmospheric CO_2 concentration by $C_A = r_C[CO_2]_A$ with $r_C = 2.13$ GtC ppm^{-1}), F_{Foss} is the anthropogenic CO_2 emission flux [GtC y^{-1}] from fossil fuel combustion and other industrial processes including cement production, F_{LUC} is the net anthropogenic emission flux [GtC y^{-1}] from land use change, and F_{BA} and F_{MA} are the net CO_2 fluxes to the atmosphere from the terrestrial biosphere and ocean [GtC y^{-1}]. The forcing fluxes $F_{\text{Foss}}(t)$ and $F_{\text{LUC}}(t)$ are externally prescribed, and F_{BA} and F_{MA} are specified functions of model state (carbon stores in atmospheric, land and ocean pools, together with temperature).

Reactive gases are gases that decay chemically in the atmosphere, such as CH_4 and N_2O. The concentration of a reactive gas X is modelled generically by

$$\frac{d[\text{X}]}{dt} = r_{\text{X}}^{-1}\left(F_{\text{X(Nat)}} + F_{\text{X(Anth)}}(t)\right) - k_{\text{X}}[\text{X}] \qquad (10)$$

with mass-concentration ratios r_{X}, fluxes F_{X} (separating natural and anthropogenic components) and atmospheric decay rates k_{X}. For most reactive gases the decay rates depend on concentrations of other entities, so the model consists of a set of coupled differential equations which are integrated forward in time. This is the foundation for atmospheric chemistry models.

Carbon cycle and atmospheric chemistry models exist at several levels of complexity. The most complex are models fully coupled to GCMs, including the full suite of physical, chemical and biological processes in the atmosphere, oceans, land and ice (cryosphere). Processes are simulated at high resolution in space and time. Models of this scope and complexity are full Earth System Models (ESMs). At a much lower level of complexity, there are a number of simplified models of the main processes represented in Equations (9) and (10). These typically run at spatially aggregated scales (lumping the whole globe or large regions) and are coupled to simple climate schemes using response-function emulations of GCM dynamics. Of a number of models in this class, the main ones used to provide results here are MAGICC and SCCM.

- MAGICC has been used in several IPCC assessments to provide emission-concentration relationships. The most recent version, MAGIC6 (Meinshausen *et al.* 2011a; Meinshausen *et al.* 2011b), is the model used to generate emissions consistent with Representative Concentration Pathways (see below). It contains detailed atmospheric chemistry and runs at hemispheric spatial aggregation.

- SCCM (Simple Carbon-Climate Model) was developed to test the robustness of relationships between cumulative emissions and temperature (Raupach *et al.* 2011). These relationships underpin the "carbon budget" approach to setting climate goals, described later.

4.2 Emission-concentration relationships for Representative Concentration Pathways

Representative Concentration Pathways (RCPs; Moss *et al.* 2010) provide the primary future emission and concentration scenarios for the IPCC Fifth Assessment Report (AR5) due in 2013. The RCP approach is fundamentally different from that used in the SRES scenarios (Nakicenovic *et al.* 2000) used in the Fourth Assessment Report (AR4) released in 2007.

The SRES (AR4) approach started with postulated emissions scenarios for the 21st century generated from a large number of Integrated Assessment Models (IAMs))(Nakicenovic *et al.* 2000). From these, particular scenarios were selected as "marker" emission scenarios and used (with an earlier version of MAGICC) to generate GHG concentrations which were in turn used to provide radiative forcings to GCMs. This approach led to controversy about the extent to which the marker scenarios were representative, and whether results from all available IAMs and SRES scenarios should be used to get the best possible picture of emissions futures as seen in 2000 (Raupach *et al.* 2007; Le Quere *et al.* 2009; Manning *et al.* 2010; Raupach and Canadell 2010).

The RCP (AR5) approach differs in several ways, the most important being that it starts from concentrations, not emissions. Just four concentration scenarios were developed (RCP3pd, RCP4.5, RCP6.0 and RCP8.5), corresponding to radiative forcings in 2100 of 2.6, 4.5, 6 and 8.5 W m^{-2}, respectively. (Scenario RCP3pd is a peak-and-decline scenario, with a maximum forcing of 3.0 W m^{-2} well before 2100). These forcings span the range from low (~2 degree warming) to severe (>4 degrees) climate change through the 21st century. The four scenarios were developed by different groups using different IAMs. Emissions for multiple species (39 in all) were then derived to match the concentration scenarios by inverting the MAGIC6 model.

The following RCP results (imaged directly from the RCP database website[5]) illustrate major aspects of emission-concentration relationships in RCP scenarios.

- Figure 7 shows RCP scenarios for total anthropogenic emissions of CO_2, CH_4 and N_2O. These emissions all rise rapidly through the 21st century for the highest-forcing scenario (RCP8.5) and fall from 2010-20 onward for the lowest-forcing scenario (RCP3pd). Other scenarios are intermediate. CO_2 emissions vary smoothly with radiative forcing through the four scenarios, but CH_4 emissions do not.

- Figure 7(suppl.) is provided to relate RCP scenarios with the earlier SRES (AR4) scenarios, for total CO_2 emissions. By this measure RCP8.5 is broadly comparable with the SRES A1FI marker scenario, RCP6 with SRES A1B, and RCP4.5 with SRES B1. The lowest RCP scenario, RCDP3pd, has no direct counterpart in the SRES suite.

- Figure 8 shows anthropogenic emissions of reactive gases and aerosol precursors for the four RCP scenarios. For these emissions, the variation among scenarios is less than for emissions of CO_2, CH_4 and N_2O (Fig. 7).

[5] For details see the RCP database: http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about

- Figure 9 shows the CO_2, CH_4 and N_2O concentrations for the four RCP scenarios. Relative to 2010 concentrations (387 ppm for CO_2, 1750 ppb for CH_4), scenario RCP8.5 gives very high concentrations of CO_2 (~930 ppm) and CH_4 (~3700 ppb) in 2100. In scenario RCP3pd, the CH_4 concentration in 2100 (~1250 ppb) is lower than in 2010 - this is the only case among the four scenarios where any of CO_2, CH_4 and N_2O decline significantly in concentration from 2010 to 2100.

- Figure 10 shows the radiative forcing for the four RCP scenarios, distinguishing the total forcing from all agents (GHGs, aerosols, ozone etc) in the upper panel, and "other" forcing (from aerosols, ozone etc) in the lower panel (see Equation (4)). The lower panel is striking because the negative "other" forcing declines rapidly from 2000 on in all scenarios, unlike the total forcing which is dominated by the GHG component. This is mainly because of decreasing negative (cooling) radiative forcing from aerosols (Section 3.2.3). The peak in negative forcing around 2000 is very strong in all scenarios, implying that the scenarios embody rapid improvements in air quality and changes in other aspects contributing to "other" forcing. Therefore there is a decrease in all scenarios in the associated net cooling effect. This is a very important projection, with the potential to make stabilisation targets more difficult to achieve (Ramanathan and Feng 2008).

- Figure 11 shows the radiative forcing as CO_2 equivalent concentrations for the four RCP scenarios, distinguishing CO_2eqTot (including all forcing agents) and CO_2eqGHG (including GHGs only). There are clear differences between these two definitions of CO_2 equivalent concentrations, with the latter being higher by up to 100 ppm in high-emission and high-concentration scenarios.

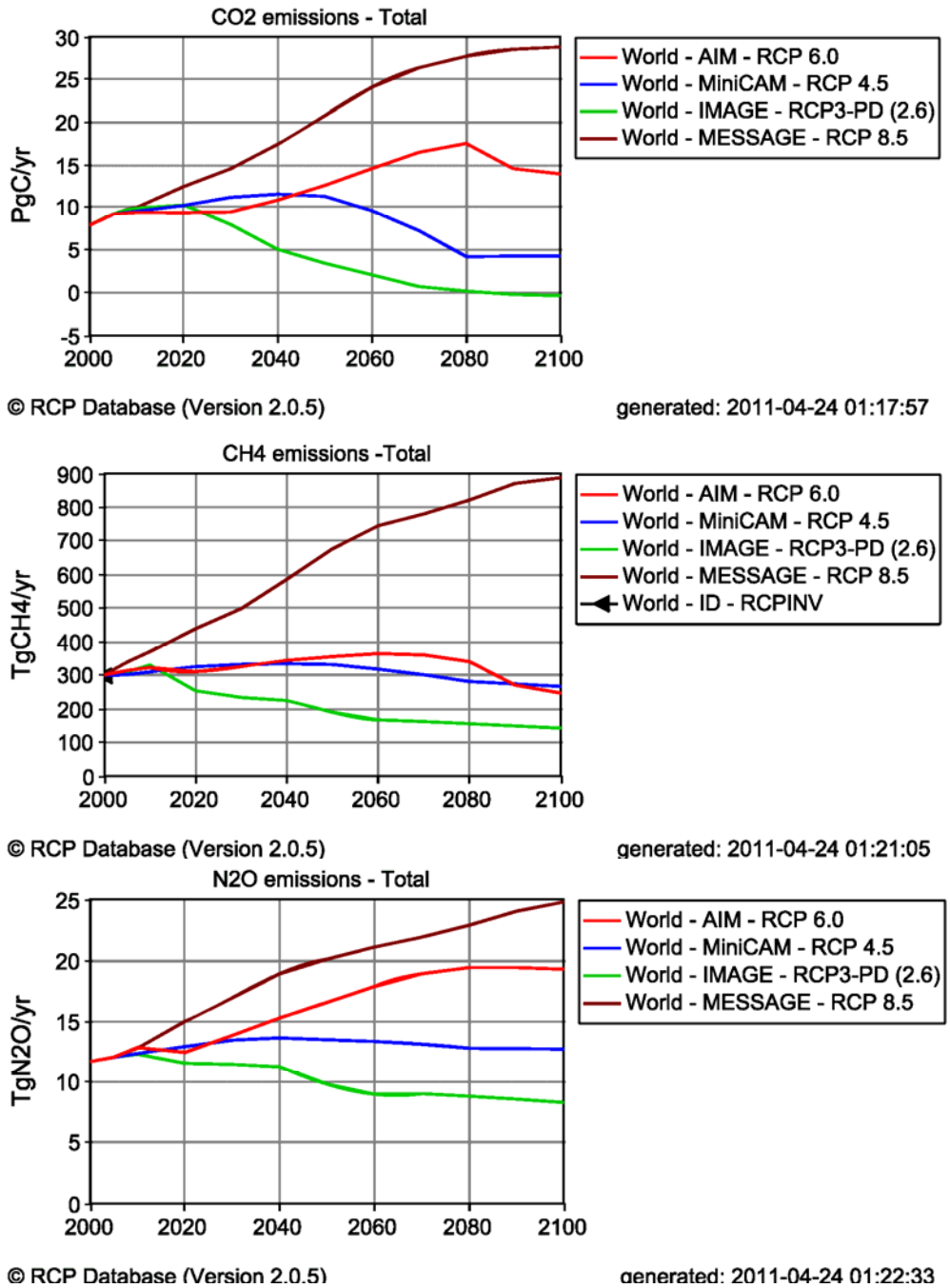


Fig. 7 Total anthropogenic emissions of CO_2, CH_4 and N_2O for four RCPs. Total CO_2 emissions include emissions from fossil fuels, other industrial sources and land use change. Source: RCP database

(http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about)

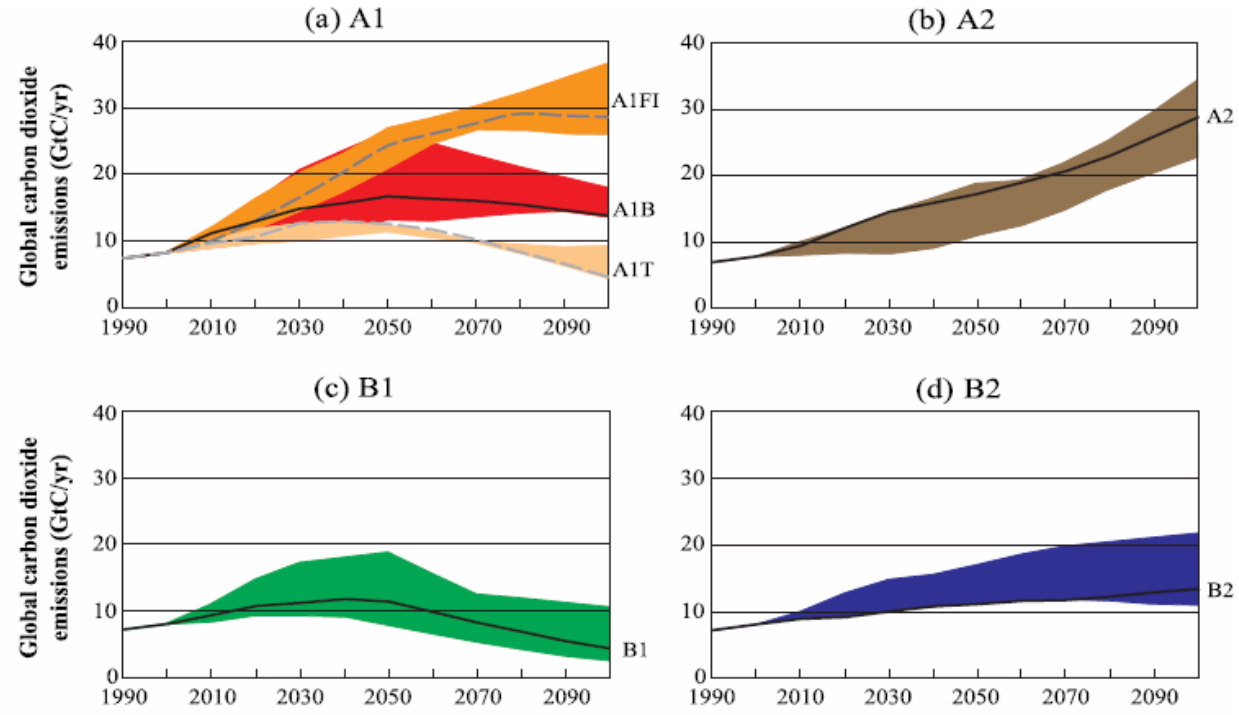


Fig. 7 (suppl.) SRES emissions scenarios for total anthropogenic CO_2 emissions from fossil fuels, other industrial sources and land use change (Nakicenovic *et al.* 2000, Summary for Policymakers, Fig. 3). This is included for comparison with RCP emissions in Fig. 7.

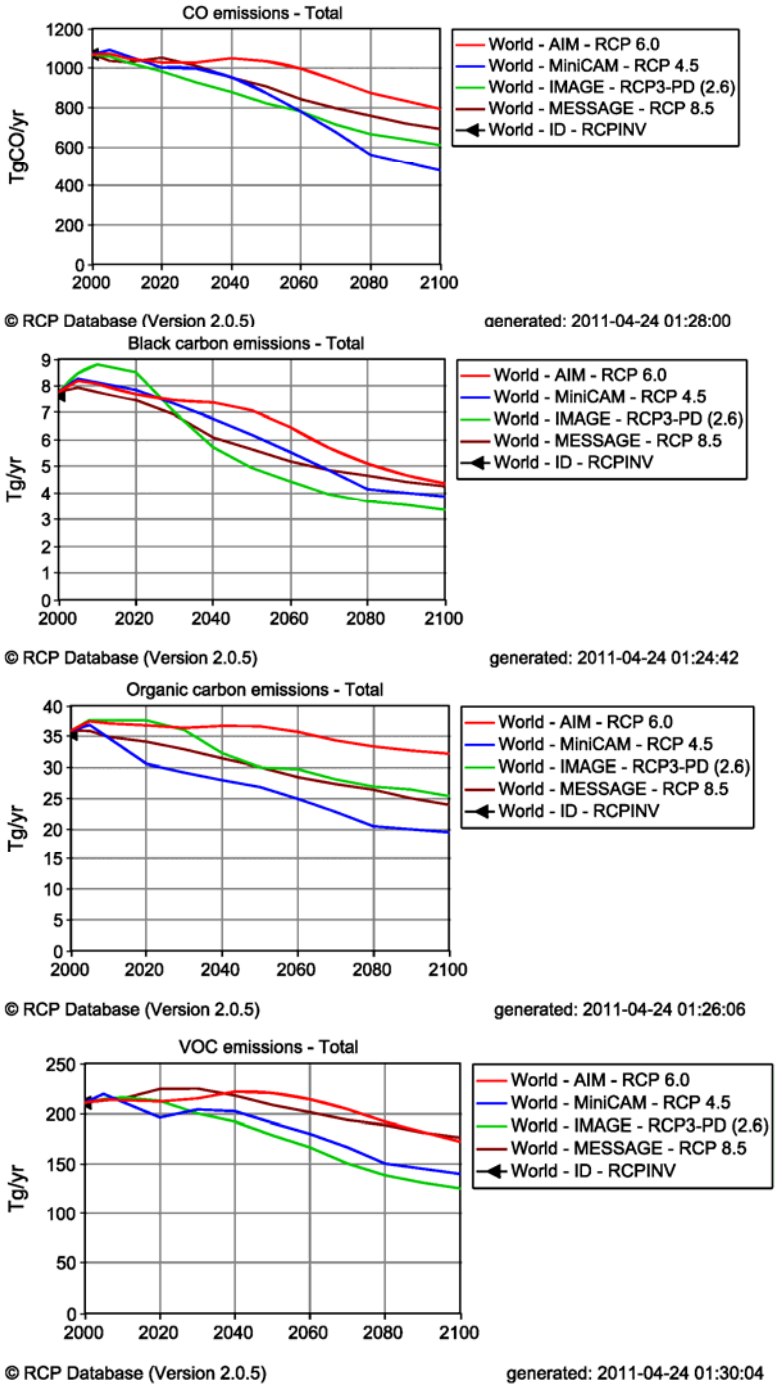


Fig. 8 Emissions of reactive gases and aerosol precursors for four RCPs. Source: RCP database (http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about)

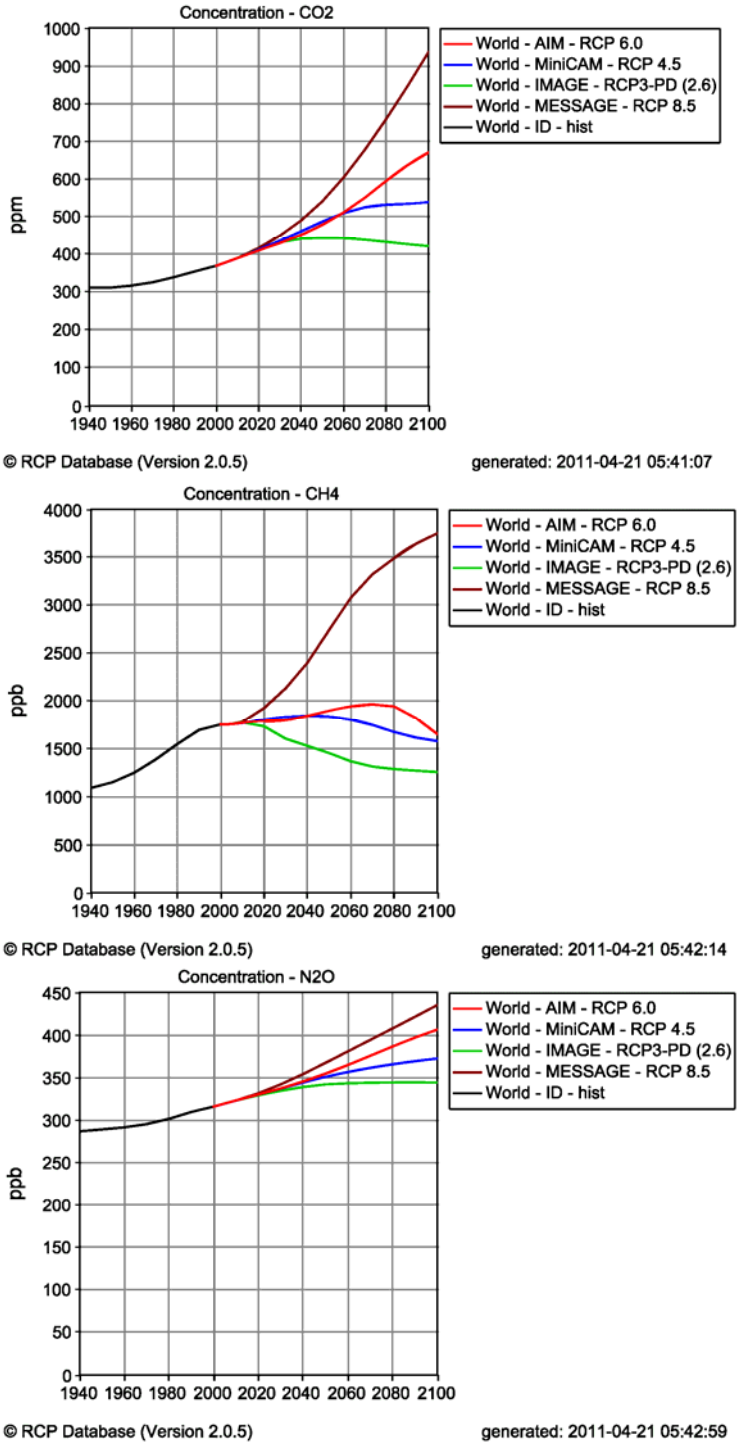


Fig. 9 CO_2, CH_4 and N_2O concentrations for four RCPs. Source: RCP database (http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about)

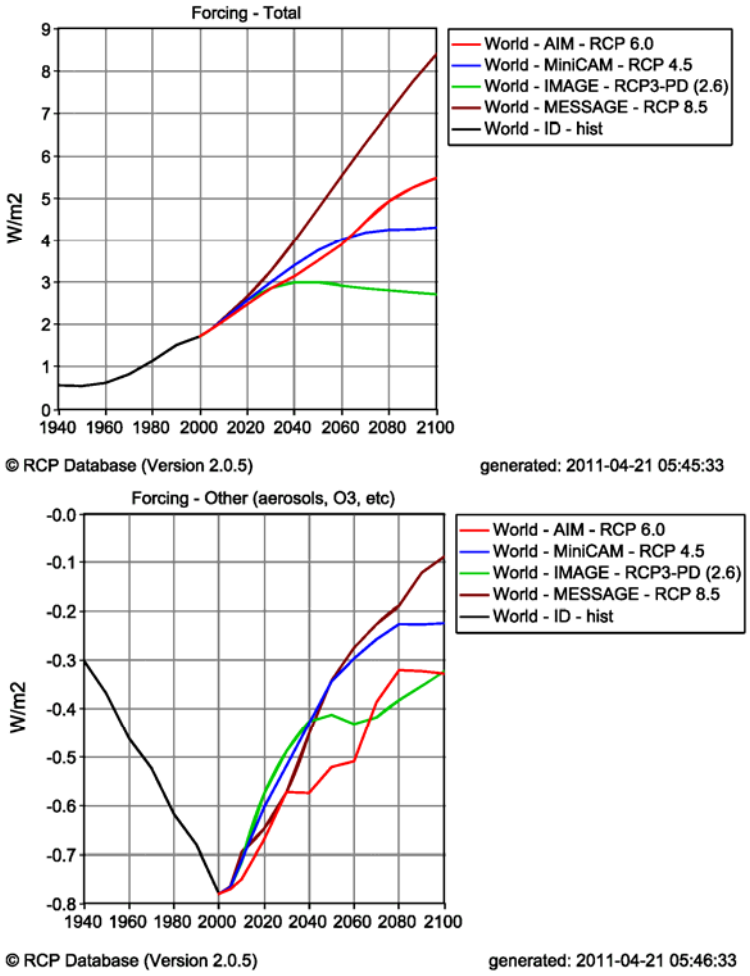


Fig. 10 Radiative forcing for four RCPs. Upper panel includes all forcing agents (GHGs, aerosols, ozone etc.). Lower panel gives (negative) radiative forcing for aerosols, ozone etc. Source: RCP database (http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about)

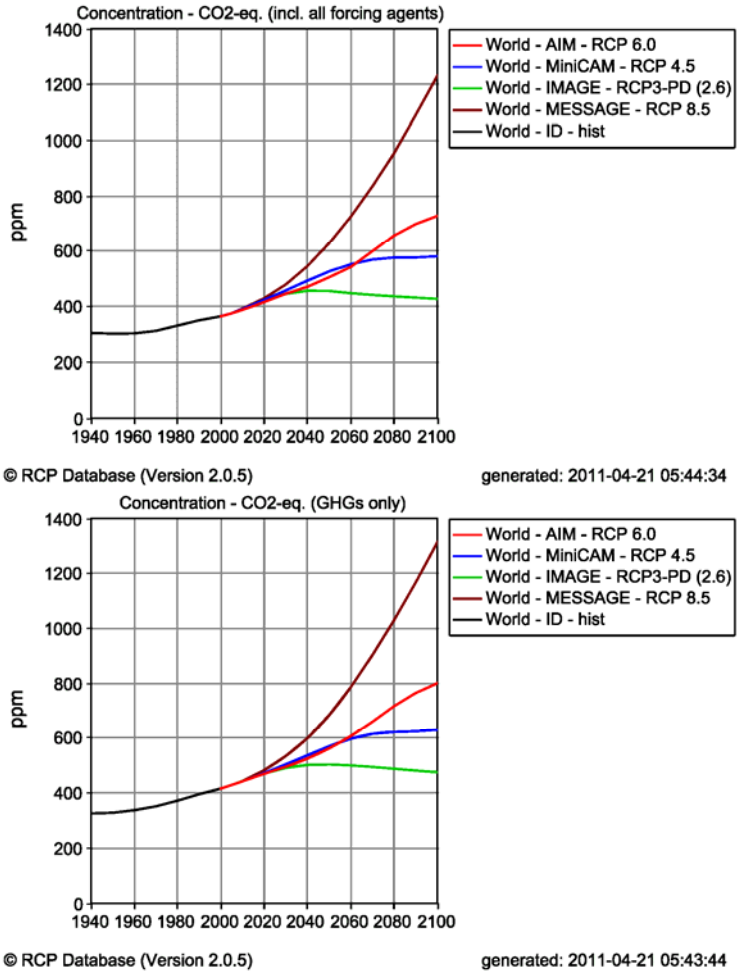


Fig. 11 Radiative forcing as CO_2 equivalent concentrations for four RCPs. Upper panel: CO_2eqTot, including all forcing agents (GHGs, aerosols, ozone etc.). Lower panel: CO_2eqGHG, including GHGs only.

Source: RCP database
(http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about)

5 CUMULATIVE EMISSION QUOTAS

5.1 The link between cumulative CO_2 emissions and peak warming

In Fig. 1, link 4 relates emissions directly to warming without passing explicitly through the intermediate steps of concentrations and radiative forcing. This link is possible because several recent papers (Allen *et al.* 2009; Meinshausen *et al.* 2009; Matthews *et al.* 2009; Zickfeld *et al.* 2009; Raupach *et al.* 2011) have established a relationship between warming above preindustrial temperatures (ΔT) and cumulative anthropogenic CO_2 emissions (Q) from fossil fuel combustion and net land use change since the start of the industrial revolution around 1750. In parallel, there is developing policy interest in the concept of "carbon budgets", or allowable quotas for emissions of CO_2 and other GHGs for a long period into the future.

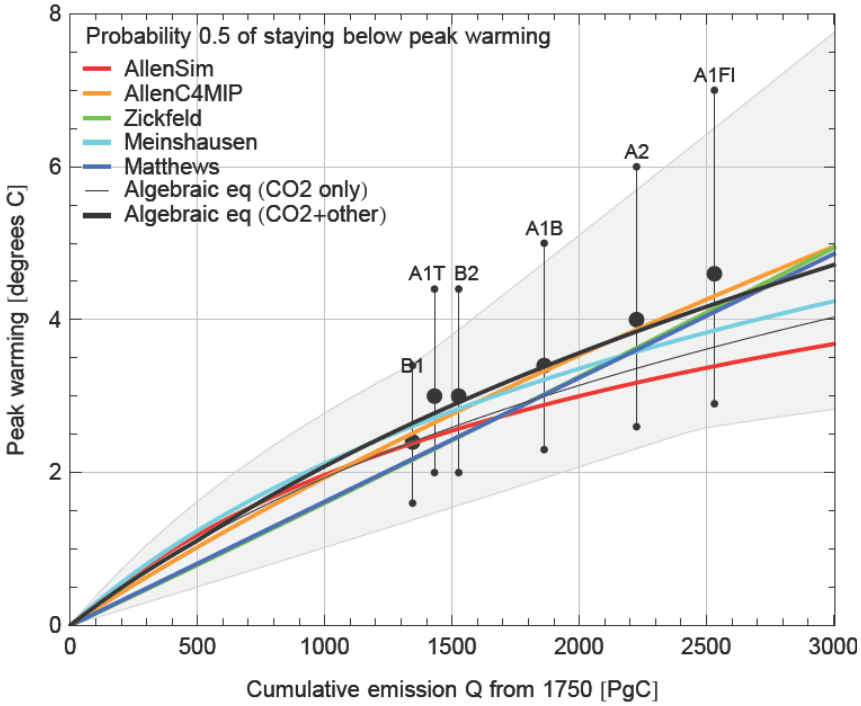


Fig. 12 Warming from preindustrial times (ΔT), plotted against cumulative carbon emissions (Q) from both fossil fuels and land use change, from 1750 onward, for cumulatively capped emissions trajectories. Coloured curves, representing the median probability for ΔT, are from Allen et al. (2009), Meinshausen *et al.* 2009, Zickfeld et al. (2009) and Matthews et al (2009). The shaded area represents the outer limit of the 17-83% confidence intervals from these studies. The process for fitting median ΔT and the probability distribution of ΔT for each study is described in Appendix A. Thin and heavy black curves are from an algebraic expression for $\Delta T(Q)$ (Raupach *et al.* 2011), respectively accounting for warming from CO_2 only and warming from CO_2, non-CO_2 GHGs and non-gaseous forcing, mainly from aerosols. Solid points with error ranges show IPCC marker scenarios for warming T(2100) in the year 2100 (IPCC 2007a), plotted against corresponding cumulative CO_2 emissions to 2100; uncertainty bars give *likely* ranges in IPCC terminology (probability 67 to 90% of an outcome within this range).

The curves in Fig. 12 show several formulations of the relationship $\Delta T(Q)$, from five papers (Allen *et al.* 2009, Meinshausen *et al.* 2009; Matthews *et al.* 2009; Zickfeld *et al.* 2009; Raupach *et al.* 2011). The curves represent median values of ΔT. The uncertainty is indicated by the grey band, which is the outer limit of the 17-83% confidence intervals from all studies. For

comparison, Fig. 12 also includes points for cumulative emissions $Q(2100)$ and warming $\Delta T(2100)$ to the year 2100, from the six IPCC AR4 marker scenarios (IPCC 2007a).

The five studies in Fig. 12 used different measures of Q and were presented in different ways, so it was necessary to fit common empirical forms to the results for all studies in order to standardise them. The process for doing this is given in Appendix A.

A simple interpretation of Fig. 12 is that cumulative emissions must be less than about $Q = 1000$ GtC[6] to have a 50% chance of keeping warming below 2 degrees. The next section looks at other probabilities). Cumulative emissions to the end of 2010 were about 540 GtC, rising at nearly 10 GtC per year (Le Quere *et al.* 2009; Friedlingstein *et al.* 2010), so more than half of a 1000 GtC quota has been used already. The other half will be used in about 50 years if annual CO_2 emissions remain at current rates, and in 35 years if emissions grow at around 3% per year as they have since 2000 (Friedlingstein *et al.* 2010; Raupach and Canadell 2010).

Figure 13 (from Raupach *et al.* 2011) indicates what lies behind the relationship between ΔT and Q. In panel (a), this shows CO_2 emissions trajectories from observations up to 2010, and from a family of smooth capped emissions trajectories from 2010 onward. These trajectories have a peak in emissions followed eventually by exponential decline, and are constructed so that the all-time cumulative CO_2 emission from both fossil fuels and land use change takes values from 1000 to 3000 GtC. Panels (b) and (c) show the resulting CO_2 concentration and temperature trajectories in a "CO_2-only world" (all other radiative forcing being ignored). Both the concentration and temperature trajectories have a peak followed by subsequent decline, but the peak in concentration occurs after the peak in emissions and the peak in temperature occurs later still. The decline in temperature after its peak is slow, particularly with high warming.

The right panels (d,e,f) of Fig. 13 show emissions, CO_2 concentration and temperature plotted against the "cumulative emission clock", the cumulative CO_2 emission $Q(t)$ up to time t. It is evident in panel (f) that the trajectories $(Q(t), \Delta T(t))$ collapse approximately to a common set of curves up to near the time of peak temperature, and that the peak temperature itself lies close to (but a little below) this common trajectory. The collapse of temperature trajectories to a common curve against the cumulative-emission clock (before the time of peak temperature) is the reason why there is an approximate relationship between cumulative emissions and peak warming.

[6] Cumulative CO_2 emissions are expressed here in GtC or Gigatonnes of carbon; 1 GtC (10^{15} grams of carbon) = (10^9 tonnes of carbon) = (1 billion tonnes of carbon); 1000 GtC is 1 trillion tonnes of carbon; this is the origin of the paper title "Towards the trillionth tonne" (Allen *et al.* 2009). Cumulative emissions in units of CO_2 mass (say $GtCO_2$) are equal to 44/12 = 3.67 times cumulative emissions in units of carbon mass, because a CO_2 molecule contains 2 oxygen atoms and has a mass 44/12 times the mass of its single carbon atom.

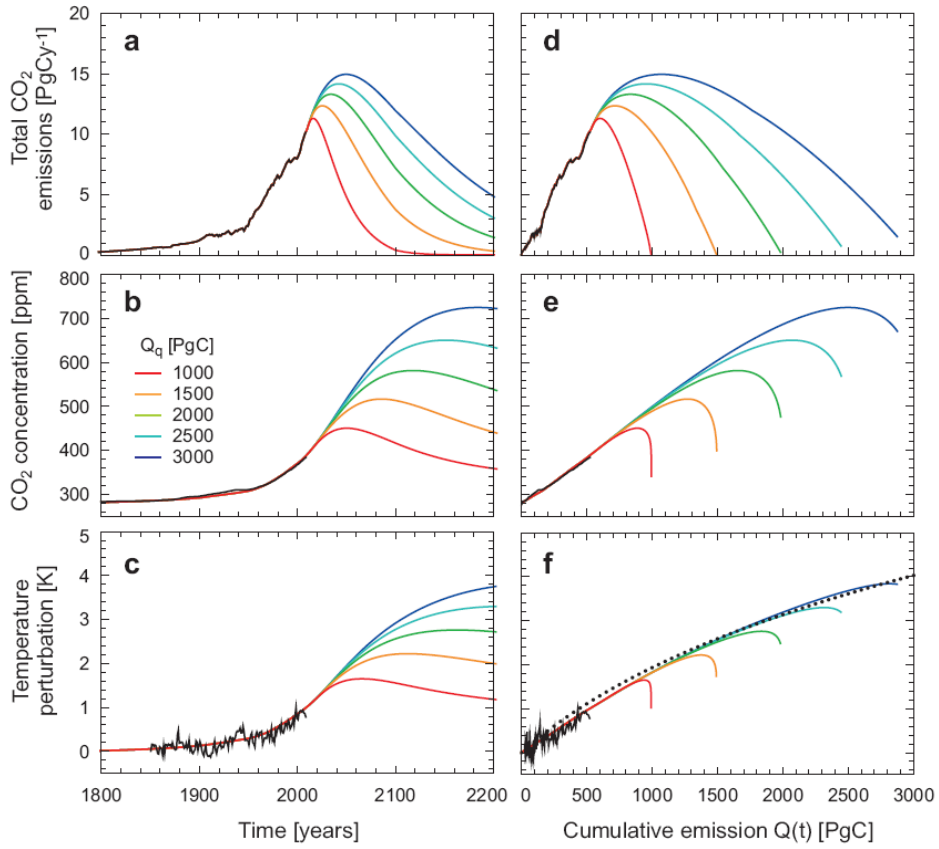


Fig. 13 Total CO_2 emissions, CO_2 concentrations and temperatures from the Simple Carbon-Climate Model (SCCM) (coloured curves), for smooth capped CO_2 emissions trajectories with all-time cumulative emission Q from 1000 to 3000 GtC and mitigation start time fixed at t_m = 2011, also shown in Fig. 14. Black curves are observations; see Appendix C in (Raupach *et al.* 2011) for data sources. Radiative forcing is from CO_2 only. Quantities are plotted against time in left, panels (a, b, c) and cumulative CO_2 emissions $Q(t)$ in right panels (d, e, f). Dashed curve is from an algebraic expression for $T(Q)$ (Raupach *et al.* 2011).

There are several important aspects to the relationship $\Delta T(Q)$ between warming and cumulative emissions. First, the relationship has been applied both to $(Q(t), \Delta T(t))$ at times t prior to the time of peak warming (t_p), and also $(Q(t_p), \Delta T(t_p))$. These relationships are actually slightly different, because the peak warming $\Delta T(t_p)$ is about 0.2 to 0.3 degC lower than the warming that would occur at the same Q on a trajectory with continuing growth in emissions (Fig. 13f).

Second, the relationship $\Delta T(Q)$ has been developed to date mainly for CO_2. Of the papers represented in Fig. 12, three (Allen *et al.* 2009, Matthews *et al.* 2009; Zickfeld *et al.* 2009) considered CO_2 only. The other two (Meinshausen *et al.* 2009; Raupach *et al.* 2011) dealt in various ways with non-CO_2 gases, but plotted ΔT against cumulative CO_2 emissions only. This assumes some relationship between CO_2 emissions, emissions of other gases, and non-gaseous radiative forcing. There is ongoing work in several groups to establish a relationship between warming and cumulative emissions of all gases contributing to warming. Later (in Section 5.3, Appendix C and the spreadsheet this report) we construct an approximate relationship from the science available at present.

Third, there is significant uncertainty in the relationship $\Delta T(Q)$, indicated by the grey band in Fig. 12. This uncertainty is comparable with the uncertainty in climate projections to 2100, as indicated by the IPCC points in Fig. 12. Several biophysical factors contribute to the uncertainty, including: (a) uncertainty in climate sensitivity (Roe and Baker 2007, Knutti and Hegerl 2008); (b) uncertainty about carbon-climate feedbacks on land and ocean CO_2 sinks

(Friedlingstein *et al.* 2006); (c) releases of carbon from disturbed pools, such as organic carbon in frozen soils (Tarnocai *et al.* 2009; Schuur *et al.* 2009), tropical peatland soils (Hooijer *et al.* 2010), other forest ecosystems (Kurz *et al.* 2008a, Kurz *et al.* 2008b), and methane hydrates on the ocean floor and beneath permafrost (Bohannon 2008); and (d) the roles of non-CO_2 gases and non-gaseous forcing, including possible future reductions in the net cooling from aerosols discussed in previous sections. While all of these uncertainties are significant, a rough ordering from the largest down is (a), followed by (c) and (d), followed by (b) (Raupach *et al.* 2011).

For all of these reasons, the relationship $\Delta T(Q)$ is an approximation. Nevertheless, its great utility is that a cumulative emission quota provides a simple, minimally ambiguous link between potential policy commitments and warming outcomes, while allowing considerable flexibility in implementation detail. In this respect it is better than emissions targets for specific years, because the timing of emissions reductions becomes secondary in importance to the overall global quota once that quota is prescribed – and in fact is largely determined by the quota, as analysed below in Section 5.2.

5.2 Emission trajectories consistent with a cumulative quota

In this section we look at properties of CO_2 emissions trajectories that satisfy a given cap or cumulative quota, leading to a warming specified in broad terms by Fig. 12.

5.2.1 A family of smooth capped emissions trajectories

To meet the constraint of a given cumulative quota, an emission trajectory must peak and then decline. The trajectory must also join smoothly with past emissions, which have grown approximately exponentially over the last century. To do this we use a family of emissions trajectories specified by a simple mathematical formula (Raupach *et al.* 2011) summarised in Appendix B. This "smooth capped" emissions trajectory (already used in Fig. 13) assumes that mitigation effort begins at a time t_m while emissions are still growing with growth rate r. Mitigation is applied at rate m (the fractional reduction in emissions per year), but does not cause an immediate reduction in emissions because initial growth must first be overcome. Therefore, mitigation causes emissions first to fall below the exponential-growth curve, then to peak and start to decline, and eventually to decline exponentially at rate m. The actual achieved mitigation rate is less than m because of the need to overcome initial growth.

The cumulative emission is a finite quantity given by the integral under the smooth capped emission trajectory. This takes the simple form

$$\frac{Q_m}{F_m} = \frac{2m+r}{m^2} \qquad (11)$$

where r is the initial emissions growth rate [y^{-1}], m is the applied mitigation rate [y^{-1}], F_m is the initial emission at time t_m and Q_m is the cumulative emission from time t_m onward. The ratio Q_m/F_m is a "quota time scale" to be discussed below.

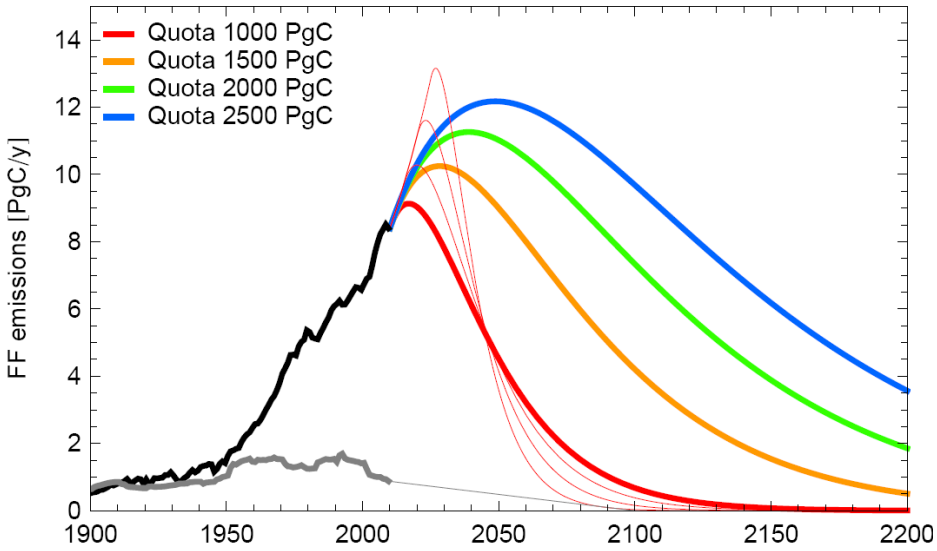


Fig. 14 Coloured curves show smooth capped trajectories for CO_2 emissions from fossil fuels and other industrial sources (F_{Foss}), from Equation (21) (Appendix B) with mitigation start time t_m = 2011.0 and initial growth rate r = 0.03 y^{-1} in F_{Foss} at time t_m. Past data for F_{Foss} are shown by the heavy black line. Past emissions from land use change (F_{LUC}) are shown by the heavy grey line, and the assumed future trajectory of F_{LUC} by the light grey line. Total (F_{Foss} + F_{LUC}) emissions integrate over all time to indicated cumulative quotas Q of 1000 (red), 1500 (orange), 2000 (green) and 2500 (blue) GtC. The three thin red curves are for Q = 1000 GtC, with delays of 5, 10 and 15 years in starting mitigation, so that mitigation begins in 2016.0, 2021.0 and 2026.0 for curves with successively higher peaks.

Figure 14 shows smooth capped trajectories for CO_2 emissions from fossil fuels (F_{Foss}) from the mathematical form (Appendix B) as coloured lines, together with past data for F_{Foss} as a heavy black line. Also shown are past emissions from land use change (F_{LUC}) as a heavy grey line, and a simple assumed future trajectory for F_{LUC} (a linear decrease to zero by 2100) as a light grey line. Total ($F_{Foss} + F_{LUC}$) emissions integrate over all time to all-time cumulative quotas Q of 1000, 1500, 2000 and 2500 GtC for the different heavy coloured curves for F_{Foss}. For all heavy coloured curves, mitigation is assumed to start immediately (t_m = 2011.0).

For a quota Q = 1000 GtC, the three thin red curves in Fig. 14 illustrate the effect of delay in starting mitigation by 5, 10 and 15 years, so that mitigation begins at t_m = 2016, 2021 and 2026. These curves have successively higher peaks and steeper decline rates after the peak.

A simple measure of the quota is provided by the ratio Q_m/F_m, the cumulative emission from the mitigation start time t_m onward (Q_m) divided by the initial emission at the time t_m (F_m). This is a "quota time scale": it is the time required to emit the quota Q_m at the steady emission rate F_m. For CO_2 emissions, the cumulative quota to stay below 2 degrees of warming with 50% probability is about 1000 GtC from the start of the industrial revolution around 1750 (Fig. 12), or 458 GtC from 2011 (because the past total cumulative CO_2 emission from fossil fuels and land use change was about 542 GtC to the end of 2010). In 2010, total CO_2 annual emissions were 9.7 GtC y^{-1}. Hence, to stay below 2 degrees of warming with 50% probability, the global quota time scale Q_m/F_m was 47 years. This is the time for which emissions can continue at the 2010 rate before the quota is exhausted. The relationship between this and other expressions of climate goal is given in Table S1 in the Summary.

In Fig. 15, several properties of smooth capped emissions trajectories are explored. Emissions are normalised with the initial emission F_m, so that the normalised emission is 1 at the mitigation start time. The quota time scale Q_m/F_m is used as a measure of the cumulative quota. In all panels the red curve is the same, and corresponds to quota time scale Q_m/F_m = 50 years

(close to the 47 years consistent with a median probability of 2 degrees of warming), mitigation delay $t_d = 0$, and initial emission growth rate $r = 0.02$ y^{-1} (slightly lower than the present growth rate in total emissions. In each panel, one parameter is varied about these reference values.

The top panel in Fig. 15 shows the effect of varying the quota, leading to curves in which the area below the curve increases and the peak emission occurs progressively later, with increase of the quota and the time scale Q_m/F_m. Note that the choice of Q_m determines the mitigation rate m through Equation (11).

The middle panel shows the effect of delaying the start of mitigation, at a constant quota and quota time scale Q_m/F_m. With delay, the peak occurs later and the decline in emissions after the peak becomes steeper. Thus, delay in starting mitigation requires a higher mitigation rate (m) to keep Q fixed. This is necessary because of the requirement that the area under the curve be the same for all curves. Delay is a "buy now, pay later" approach to the "carbon budget" represented by the quota.

Another attribute of the delay curves (middle panel in Fig. 15) is that all curves coincide, passing approximately through the same point, at about 35 years after the start of mitigation without delay. At this "pivot time" the emission is about 0.6 of the initial emission, irrespective of the delay in starting mitigation. With delay, more rapid declines in emission are needed after the pivot time. A similar feature is seen in Fig. 14. In flux units, the implication is that, irrespective of delay, fossil-fuel CO_2 emissions must fall to about 5.5 GtC y^{-1} by around 2045 if an all-time global quota of 1000 GtC is to be achieved.

This pivot time depends on the quota, and thence on the temperature target through the relationship shown in Fig. 12. The above values are appropriate for a quota of 1000 GtC or a quota time scale Q_m/F_m of about 50 years, consistent with a 50% chance of keeping warming to less than 2 degrees. With increase in the temperature target, the overall quota Q and the quota time scale Q_m/F_m, the pivot time occurs later and at a higher normalised emission.

The bottom panel in Fig. 15 shows the effect of variation of the initial emission growth rate r. This has a smaller effect than that of delay, but also shows an approximate coincidence of curves after about 35 years (for time scale $Q_m/F_m = 50$ years).

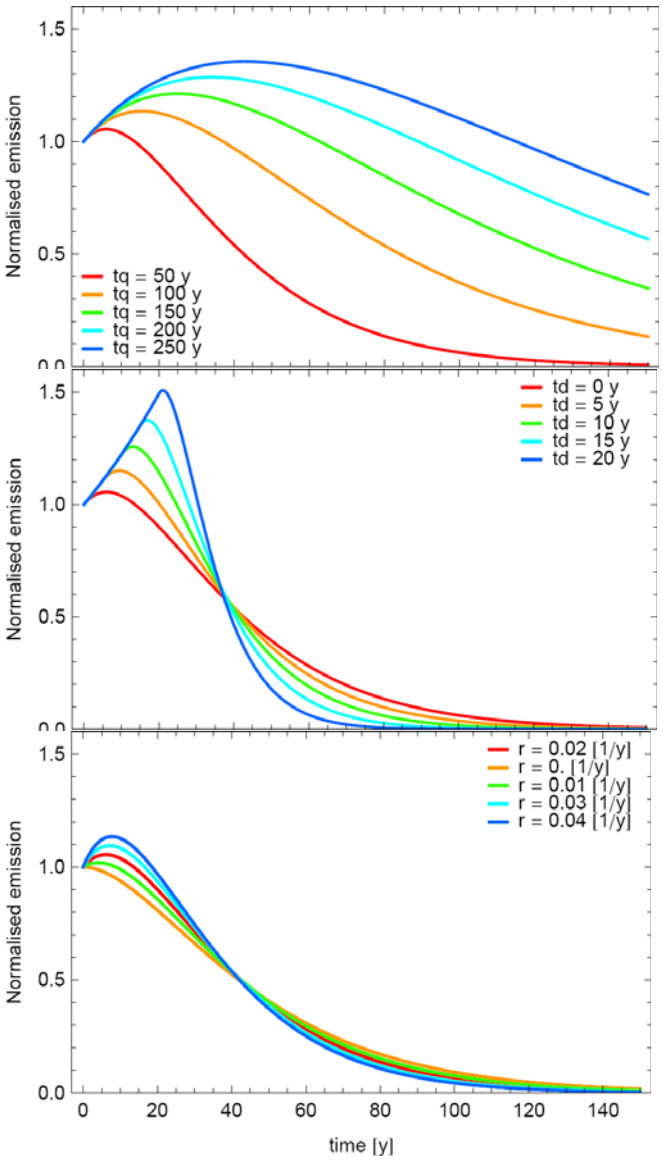


Fig. 15 Smooth capped emissions trajectories from Equation (21), Appendix B, plotted against time from the start of mitigation. The emissions are normalised with the initial emission F_m, so that the normalised emission is 1 at the mitigation start time. In all panels the red curve is the same, and corresponds to quota time scale Q_m/F_m = 50 years, mitigation delay t_d = 0, and initial emission growth rate r = 0.02 y^{-1}. In each panel, one parameter is varied about these reference values. Top panel shows the effect of varying the quota Q_m (expressed as the quota time scale Q_m/F_m) through values 50, 100, 150, 200 and 250 years (corresponding to warmings of 2.0, 2.8, 3.6, 4.3 and 5.0 degrees, from interactive use of Table S1). The choice of Q_m determines the mitigation rate m through Equation (11). Middle panel shows the effect of delaying the start of mitigation, by a delay t_d = 0, 5, 10, 15 or 20 years. Bottom panel shows the effect of variation of the initial emission growth rate r through values 0, 0.01, 0.02, 0.03 and 0.04 y^{-1}.

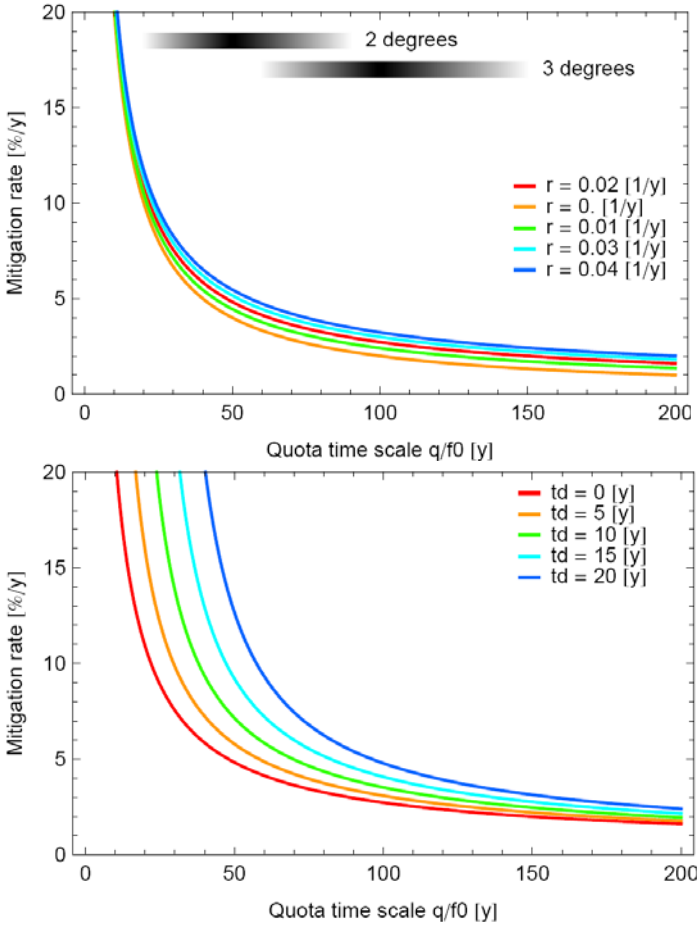


Fig. 16 Variation of mitigation rate m with quota time scale Q_m/F_m, for smooth capped emissions trajectories from Equation (21), Appendix B, as plotted in Figs 14 and 15. The red curve in both panels is for initial emission growth rate $r = 0.02$ y^{-1} and delay $t_d = 0$ (reference values). In the upper panel, r is varied through the values shown; in the lower panel, t_d is varied. The bars in the upper panel indicate an approximate range of mitigation time scales corresponding respectively to 2 and 3 degrees of warming, from Fig. 12, under assumptions given in the text.

5.2.2 The required mitigation rate to meet a given quota

Figure 16 shows the required mitigation rate m to meet a range of quotas, expressed as the quota time scale Q_m/F_m. The red curve in both panels is for initial emission growth rate $r = 0.02$ y^{-1} and delay $t_d = 0$ (reference values). In the upper panel, r is varied among the curves; in the lower panel, t_d is varied. The bars indicate an approximate range of mitigation time scales corresponding respectively to 2 and 3 degrees of warming[7]. As the quota decreases, the required mitigation rate m increases sharply: for a quota consistent with 2 degrees of warming the required m is of order 5% y^{-1} (range3 to 10) and for a quota consistent with 3 degrees, m is of order 3% y^{-1} (range 2 to 5). Higher rates m are needed with delay in starting mitigation (lower panel).

[7] These ranges assume all-time quotas $Q \sim 1000$ (700, 1400) GtC as the requirement for staying below 2 degC warming, and $Q \sim 1500$ (1100, 2000) GtC as the requirement for staying below 3 degC, from Fig. 12 (ranges in brackets), from which the quota time scale Q_m/F_m is evaluated by taking $Q_m = Q - 540$ GtC and $F_m = 9.3$ GtC y^{-1}.

A global mitigation rate of 5% y^{-1}, sustained for many decades, is greater than almost all observed regional emissions reduction rates for energy transitions over the last several decades. These include the managed energy decarbonisations in Sweden and France in the early 1980s (reductions of 4 to 5% per year for a few years) and the collapse of the former Soviet Union in the 1990s (reductions of around 7% per year for a few years, accompanied by widespread hardship). However, these examples have always involved regional decarbonisation as a side effect of some other event or process, not an intentional policy goal.

Figure 17 shows the variation of the time of maximum emission (measured from the time at which mitigation is started without delay). The time of maximum emission rises steadily with increase in the quota, as foreshadowed in Fig. 14.

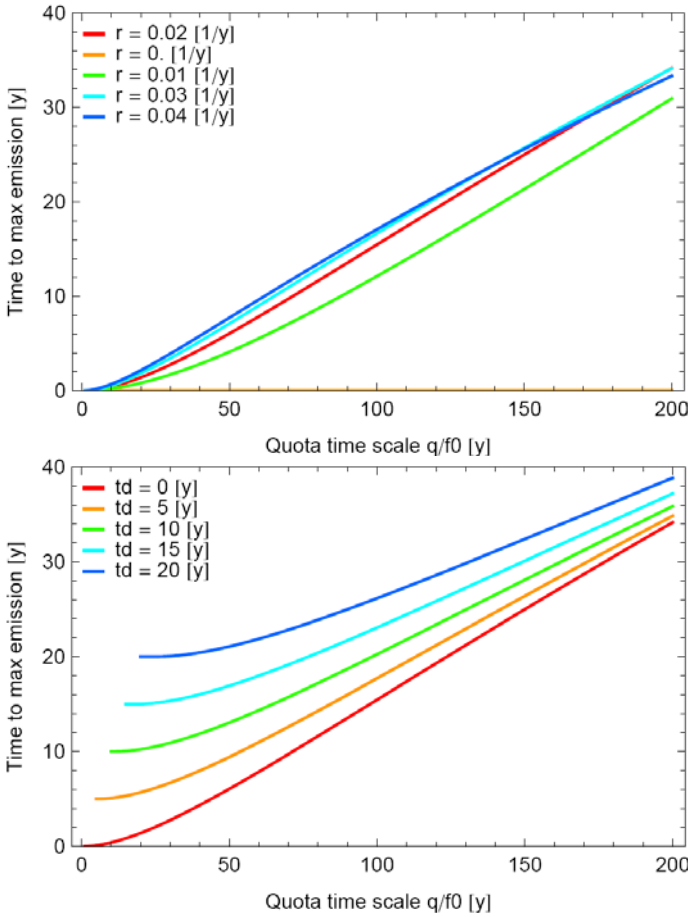


Fig. 17 Variation of time from the start of mitigation to the time of maximum emission, plotted against quota time scale Q_m/F_m, for smooth capped emissions trajectories from Equation (21), Appendix B, as plotted in Figs. 14 and 15. The red curve in both panels is for initial emission growth rate r = 0.02 y^{-1} and delay t_d = 0 (reference values). In the upper panel, r is varied through the values shown; in the lower panel, t_d is varied.

5.2.3 Emissions reductions in particular years

Recent negotiations and policy discussions have placed much emphasis on emissions reductions by particular years such as 2020 and 2050 (which we will refer to as "assessment years" in the following). The family of smooth capped emissions trajectories shown in Figs. 14 and 15 provides a way of relating these year-based emissions reductions to cumulative quotas, and thence to temperature targets via the relationship shown in Fig. 12.

Figure 18 shows global emissions in the assessment years 2020, 2050 and 2070 (upper, middle and lower panels) as a fraction of emissions in the mitigation start year 2010. The horizontal axis is the all-time cumulative quota Q for CO_2 emissions in GtC, with bars indicating approximate ranges of Q corresponding to 2 and 3 degrees of warming, from Fig. 12. Coloured lines represent the effects of delaying the start of mitigation by 0, 5, 10, 15 and 20 years after 2010.

Figure 18 is constructed for CO_2 emissions. We expect that broadly similar curves will apply for total greenhouse gas emissions, but the details and exact reduction targets will change somewhat. This is the subject of ongoing work.

Figure 18 illustrates two main features. First, global emissions in the assessment year 2020 have little relationship with long-term quotas (Fig. 18, upper panel), and likewise with temperature outcomes. Second, emissions in the assessment year 2050 (as a fraction of emissions in an initial base year) become nearly independent of delay in starting mitigation at a cumulative quota Q of about 1100 GtC (Fig. 18, middle panel); in other words, all the coloured lines approximately converge at $Q \approx 1100$ GtC. This Q value corresponds to a median peak warming of about 2.2 degrees (Fig. 12). Likewise, fractional emissions fractional emissions in the assessment year 2070 become nearly independent of delay at $Q \approx 1500$ GtC (Fig. 18, lower panel), corresponding to a warming of about 2.8 degrees. These convergences mean that the year 2050 is an approximate "pivot time" for cumulative emissions $Q \approx 1100$ GtC, and 2070 is an approximate pivot time for $Q \approx 1500$ GtC.

For a peak-and-decline emissions trajectory with fixed cumulative emissions Q, the pivot time is the time at which emissions are most nearly independent of delay, so that trajectories with different delays approximately converge at the pivot time. (The pivot time was introduced above in discussing the middle panel of Fig. 15). The existence of such an approximate convergence is a necessary consequence of *any* peak-and-decline trajectory with fixed cumulative emissions, because delay means more emissions early (before the pivot time) in exchange for reduced emissions later (after the pivot time). The pivot time is the time at which these two factors approximately balance. While Fig. 18 (along with Figs. 14 and 15) have been generated with a particular family of emissions trajectories described in Appendix B, we expect that other families of emissions trajectories would produce similar behaviour.

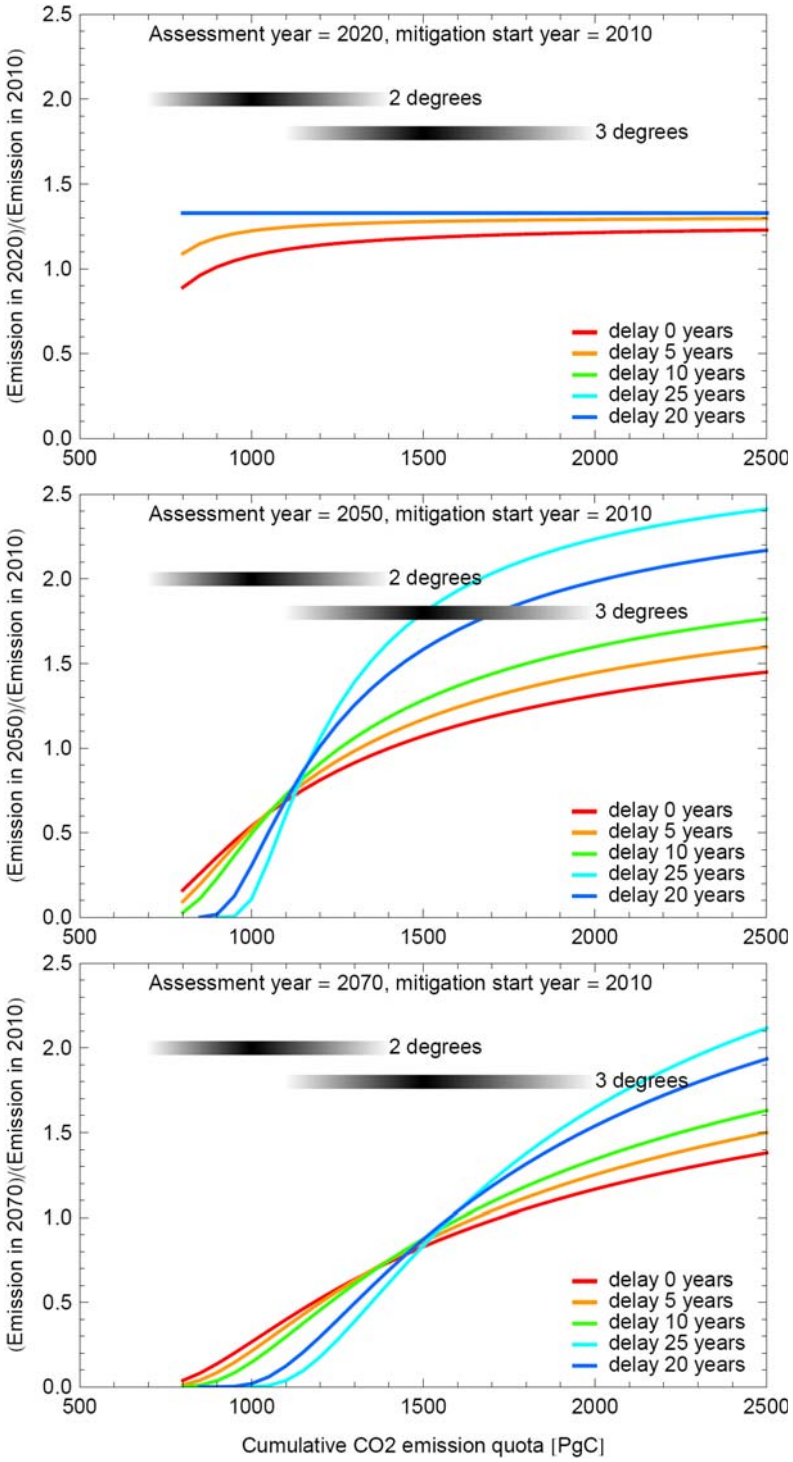


Fig. 18 Emissions in years 2020, 2050 and 2070 (upper, middle and lower panels) as a fraction of emissions in 2010, plotted against the cumulative quota for CO_2 emissions in GtC (horizontal axis), with different coloured lines representing the effects of delaying the start of mitigation by 0, 5, 10, 15 and 20 years from 2010. These results are based on smooth capped emissions trajectories from Equation (21), Appendix B, as plotted in Figs. 14 and 15. Bars indicate approximate ranges of cumulative emissions quotas corresponding to 2 and 3 degrees of warming, from Fig. 12.

5.3 Cumulative emissions quotas including non-CO_2 radiative forcing

The link between cumulative emissions and peak temperature has so far been developed almost entirely for CO_2, and the extension to multiple GHGs is still a question of active research. The basic idea is to define a "cumulative CO_2 equivalent emission" for multiple GHGs:

$$Q_{\mathrm{GHG}} = Q_{\mathrm{CO2}} + \sum_{\substack{\mathrm{nonCO2} \\ \mathrm{GHGs}}} w_n Q_n \qquad (12)$$

where Q_n is the cumulative emission for non-CO_2 gas n in mass units (such as gigatonnes of gas) and w_n is a weighting factor. These weights are conventionally defined as global warming potentials (GWPs; see below). The unit of Q_{GHG} is mass in "carbon equivalent emissions", or GtCeqEmis. Alternatively, Q_{GHG} can be measured as a mass in "CO_2 equivalent emissions", or $GtCO_2eqEmis$, where 1 $GtCO_2eqEmis$ = 3.67 GtCeqEmis (noting that 3.67 = 44/12, the ratio of the molecular masses of CO_2 and C).

It is critical to note the difference between emission equivalence and concentration equivalence. The general purpose of CO_2 equivalence is to bring CO_2 and other anthropogenic influences on climate to a "common currency", but this currency is different for emissions and concentrations. Concentration equivalence (Equation (2)) expresses how *concentrations* of different entities already in the atmosphere contribute to radiative forcing, thence climate change. Emission equivalence (Equation (12)) expresses how anthropogenic *emissions* of different entities contribute to climate change, over periods from years to centuries. The weights determining concentration equivalence and emission equivalence for different gases are quite different.

The GWP for a given GHG is defined as the ratio of the *cumulative* radiative forcing (RF) from the *instantaneous* release of 1 kg of that gas to the cumulative RF from the instantaneous release of 1 kg of CO_2 (IPCC 2001, p385). The cumulative RF is calculated over a time interval called the time horizon, with the instantaneous releases occurring at the beginning of that interval. Another view of the GWP is that it is the ratio of the *instantaneous* RF at the end of the time interval from a *steady* release of a GHG through the time interval to the instantaneous RF at the end of the time interval from a steady release of CO_2 through that interval. These two views of the GWP are equivalent, but the latter view is easier to translate into policy guidelines.

The question of the weights w_n in Equation (12) is still open scientifically, and is the subject of ongoing work. As a *temporary* placeholder, we identify the weights w_n with 100-year GWPs (see IPCC 2007b p212 for tables of GWPs for many gases).

6 DISCUSSION

6.1 Climate goals and scientific uncertainty

In this section we explore how climate goals are influenced by uncertainty in the science of climate change. In other words, how can climate goals be stated in the language of probability and risk?

Uncertainty in climate science is widely recognised (IPCC 2001; IPCC 2007a; IPCC 2007b), and is the subject of a great deal of effort by the climate community; see (AAS 2010) for a brief discussion of major uncertainties.

Here we restrict consideration of uncertainty to its implications for the relationship $\Delta T(Q)$ between global warming and cumulative CO_2 emissions (Fig. 12). All studies contributing to Fig. 12 (Allen *et al.* 2009, Meinshausen *et al.* 2009; Matthews *et al.* 2009; Zickfeld *et al.* 2009; Raupach *et al.* 2011) provided information on uncertainty, expressed as the probability density function PDF($\Delta T|Q$). For the first four of these studies, we fitted PDF($\Delta T|Q$) to results from carbon-climate models, assuming a log-normal form (this was not done for the fifth study because a different approach to uncertainty was taken there). The process is described in Appendix A. Figure 19 shows the fitted probability density function PDF($\Delta T|Q$) at $Q = 1000$ and 2000 GtC, from the first four studies.

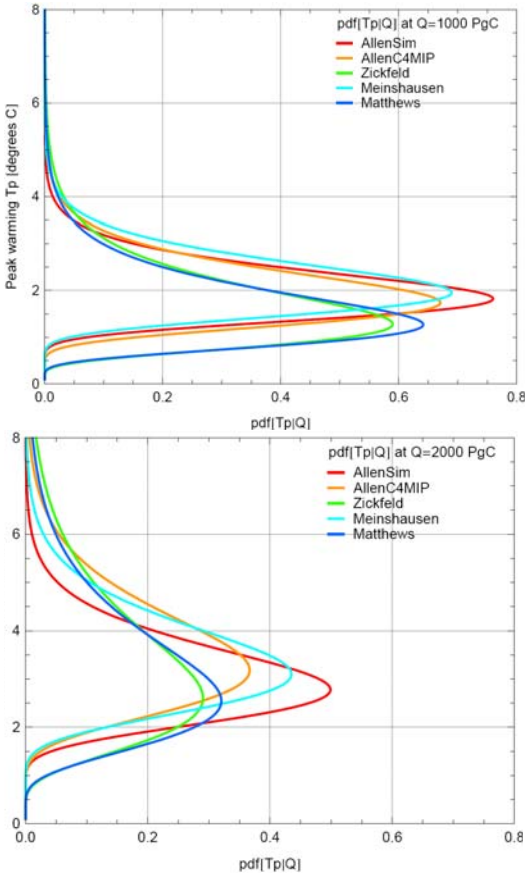


Fig. 19 Probability distributions for ΔT, the warming from preindustrial times, at Q = 1000 and 2000 GtC (left and right panels), where Q is the cumulative carbon emission from both fossil fuels and land use change from 1750 onward. Coloured curves are from Allen et al. (2009) (two curves from their Figures 2 and 3), Meinshausen *et al.* 2009, Zickfeld et al. (2009) and Matthews et al (2009).

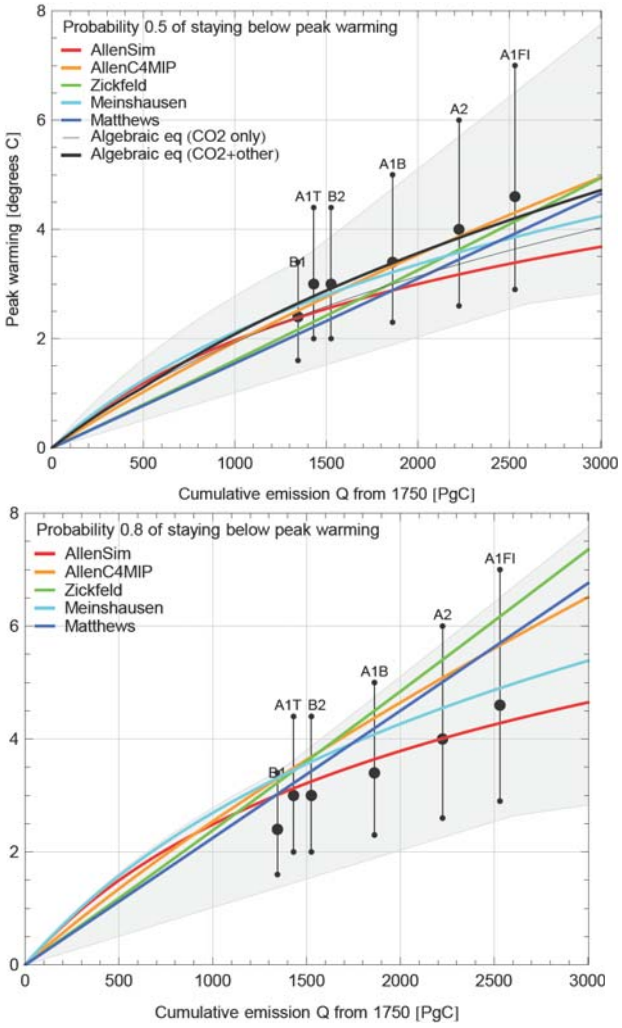


Fig. 20 Warming from preindustrial times (ΔT), plotted against cumulative carbon emissions (Q) from both fossil fuels and land use change, from 1750 onward. Left and right panels plot ΔT values at probabilities 0.5 and 0.8, respectively, in the cumulative probability distribution for ΔT. These are the warmings ΔT such that, at the Q value on the horizontal axis, there is a 50% chance (left panel) or an 80% chance (right panel) of staying below that warming. The left panel reproduces Fig. 12 for comparison. Descriptions of curves and points are given in the caption for Fig. 12.

The probability distribution PDF($\Delta T|Q$) enables calculation of the warming ΔT such that, at any given Q value, there is a specified probability P of staying below that warming. For each study, these ΔT values are plotted against Q in Fig. 20, at $P = 0.5$ and $P = 0.8$ (left and right panels). When $P = 0.5$, the resulting values of ΔT are median values as in Fig. 12, so the left panel of Fig. 20 is identical to Fig. 12 (it is reproduced here to facilitate comparison). The right panel of Fig. 20 shows the warmings ΔT such that, at the Q value on the horizontal axis, there is an 80% chance of staying below that warming (compared with a 50% chance in the left panel).

The broad conclusion from Fig. 20 is that increasing the requirement for confidence in climate change outcomes has a large effect on required quotas Q. For a 50% chance of staying below 2 degrees of warming, the quota is about 1000 GtC; for an 80% chance, it is about 700 GtC (as a rough average over the studies). In broad terms, increasing the requirement for confidence in climate change outcomes from 50% to 80% is equivalent to lowering a 2 degree temperature target by over 0.5 degrees, and a 3 degree temperature target by about 0.7 degrees.

6.2 National mitigation commitments and implications for global emissions

Here we compare the global targets outlined in previous sections with likely global emissions in 2020 from present trajectories and the Copenhagen Accord (2009) targets by parties to the UNFCCC (89 countries plus the European Union). A voluntary framework for emission reduction targets was established as part of the Copenhagen Accord during the 15th Conference of the Parties in December 2009, and agreed in 2010 at Cancun. The Accord invited Annex 1 Parties (developed countries) to submit emission reduction targets for 2020 and non-Annex 1 Parties (emerging economies and developing countries) to commit to mitigation actions.

Table 1 Mitigation pledges for some major Annex I countries and regions, and consequences for reductions in emissions in 2020. Orange-shaded column shows pledges as submitted to the UNFCCC in response to the Copenhagen Accord [http://unfccc.int/meetings/cop_15/copenhagen_accord/items/5264.php]. Yellow shaded columns show actual emissions in 1990 and forecast emissions in 2020 under a Business as Usual (BAU) scenario. Green and blue shaded columns show the emissions reductions required by low pledges (green) and high pledges (blue), referred to 1990 as a common reference year and to BAU emissions in 2020. A negative reduction target implies an increase in emissions. Yellow, green and blue columns from (Den Elzen *et al.* 2011). (*) For comparison purposes, data for the Oceania region show reduction targets excluding CO_2 emissions from land use change, a component that is part of the Australian target. Including emissions from land use change, Australia's emissions would increase the reduction target for the high pledge from 12% to 23% below 1990 levels (Den Elzen *et al.* 2011).

Country or region	**Reduction pledge from submission to UNFCCC (with reference year nominated by country)**	***GHG emissions excluding LUC ($GtCO_2eqGHG$)***		***Reduction target: Low pledge***		***Reduction target: High pledge***	
		1990	***2020 BAU***	***Below 1990***	***Below 2020 BAU***	***Below 1990***	***Below 2020 BAU***
Canada	17% (2005)	0.6	0.8	–3%	19%	–3%	19%
USA	17% (2005)	6.1	7.6	3%	23%	3%	23%
EU27+	20%; 30% (1990)	5.6	5.1	20%	13%	30%	24%
Japan	25% (1990)	1.3	1.3	25%	31%	25%	31%
Russia	15-25% (1990)	3.3	2.2	15%	–35%	25%	–19%
Ukraine	20% (1990)	1.1	0.5	18%	–73%	19%	–73%
Oceania*		0.5	0.8	–10%	23%	12%	40%
Australia	5-15%; 25% (2000)						
NZ	10-20% (1990)						
Total Annex I		18.5	18.3	**12%**	**11%**	**18%**	**17%**

Table 2 Emission reduction targets and BAU baselines of the seven largest emitting emerging economies, from Copenhagen Accord mitigation action plans. A negative reduction target implies an increase in emissions. Sources: Copenhagen Accord Appendix II

[http://unfccc.int/meetings/cop_15/copenhagen_accord/items/5265.php] and (Den Elzen *et al.* 2011).

Country	**2020 BAU emissions ($GtCO_2eq$GHG)**	**Pledged target**			
		Low pledge		**High pledge**	
		$GtCO_2eq$	**Below 2020 BAU**	**$GtCO_2eq$**	**Below 2020 BAU**
China	13.8	13.0	6%	13.0	6%
India	3.4	3.4	–1%	3.3	3%
Brazil (including land use CO_2)	2.4	1.6	37%	1.5	38%
Mexico (including land use CO_2)	0.9	0.8	6%	0.6	30%
South Africa	0.6	0.5	12%	0.5	12%
South Korea	0.9	0.7	30%	0.7	30%
Indonesia (including land use CO_2)	2.5	1.8	26%	1.5	41%
Total emerging economies	**24.5**	**21.8**	**11%**	**21.0**	**14%**
Other Non-Annex I countries	9.8	9.8	0%	9.8	0%
Land use CO_2 emissions outside Brazil, Indonesia and Mexico	1.7	1.7	0%	1.7	0%
Total Non-Annex I	**36.0**	**33.3**	**7%**	**32.6**	**10%**

Table 1 shows the commitments made to date by a selection of Annex 1 countries, together with the corresponding estimated emissions reductions using a common base year of 1990 (following Den Elzen *et al.* 2011). Many Annex 1 countries have provided two mitigation targets, a lower target as an unconditional commitment and a higher target associated with higher global ambition reflected in stronger commitments by other countries.

From emission targets and mitigation actions like those summarised in Table 1, it is not easy to estimate the overall effect on global emissions. An important complication is that "mitigation actions" currently promised from many developing countries are complex and require a number of assumptions to translate them into actual emission reductions or emissions avoided. Critical cases are China and India, who have promised mitigation actions in terms of energy or carbon efficiency (energy or carbon emissions per economic growth unit) which are tied to GDP; thus, their absolute emissions are contingent on their GDP growth trajectories. This is important because non-Annex 1 Parties were responsible for 57% of global emissions in 2009 (Friedlingstein *et al.* 2010), with China and India as leading contributors. The non-Annex-1 share of global emissions is expected to grow quickly to 2020 and beyond. For non-Annex 1 countries, mitigation actions submitted in response to the Copenhagen accord can be found its Appendix II. Table 2 shows an interpretation of those actions for emission reductions against business as usual (BAU) emissions (Den Elzen *et al.* 2011).

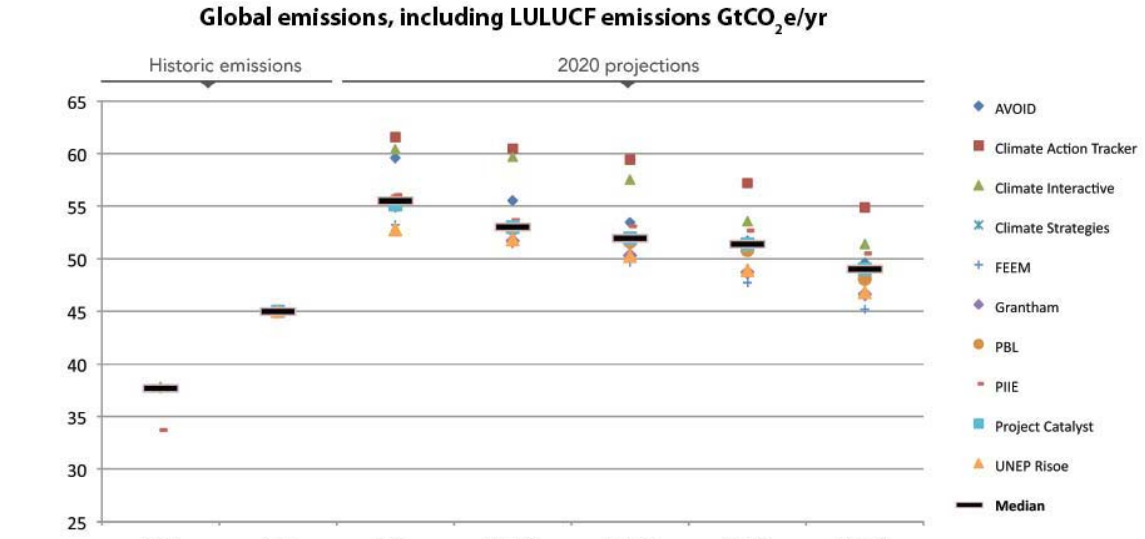
A number of studies have estimated the likely impact of the Copenhagen Accord mitigation pledges on global anthropogenic emissions (European Climate Foundation 2010; Stern and

Taylor 2010; Den Elzen *et al.* 2010; Den Elzen *et al.* 2011; UNEP 2010; see also the Climate Action Tracker, www.climateactiontracker.org, for ongoing assessments).

Of these studies, the UNEP analysis (UNEP 2010) is the most comprehensive study to date. The strength of this work is that it reviewed the analyses of 9 modelling groups, thereby captures a broad range of modelling approaches and assumptions required to interpret country-level commitments. Four cases were considered:

1. *Unconditional pledges, lenient rules:* Countries choose their lower promised levels of mitigation (unconditional commitment, not tied to what other countries do) and are subject to lenient accounting rules; for example, Annex I countries use all surplus emission units and lenient credits for LULUCF (land use, land use change and forestry).
2. *Unconditional pledges, strict rules:* Countries choose their lower levels of mitigation and are subject to strict accounting rules.
3. *Conditional pledges, lenient rules:* Countries choose higher, more aggressive mitigation targets with lenient accounting rules.
4. *Conditional pledges, strict rules:* Countries choose higher, more aggressive mitigation targets and are subject to strict accounting rules.

Figure 21 shows the individual model estimates for each of the four cases in the UNEP analysis, and tabulates various emission estimates. The business as usual scenario (baseline) is an increase in global emissions from 45 $GtCO_2eqGHG\ y^{-1}$ in 2005 to 56 $GtCO_2eqGHG\ y^{-1}$ in 2020. The analysis estimates that global emissions would be 56 $GtCO_2eqGHG\ y^{-1}$ (20^{th}-80^{th} percentile range: 54-60) by 2020 under a business as usual scenario, 53 $GtCO_2eqGHG\ y^{-1}$ (range: 52-57) under the low emission commitments and lenient implementation, and 49 $GtCO_2eqGHG\ y^{-1}$ (range: 47-51) under the highest emission commitments and strict implementation.



	1990	2005	2020 Business-as-usual	(Case 1) 2020 Unconditional pledges, Lenient rules	(Case 2) 2020 Unconditional pledges, Strict rules	(Case 3) 2020 Conditional pledges, Lenient rules	(Case 4) 2020 Conditional pledges, Strict rules
n²	4	9	9	9	9	9	9
High	37.9	45.0	61.6	60.6	59.4	57.2	54.9
80th	37.8	45.0	59.9	57.1	55.1	53.0	50.9
Median	37.7	45.0	55.5	53.0	51.9	51.4	49.0
20th	36.1	45.0	54.3	51.8	50.3	48.8	46.7
Low	33.7	45.0	52.8	51.4	49.7	47.7	45.2

Fig. 21 Global emissions in 2020 according to four pledge cases from country depositions in response to the Copenhagen Accord (UNEP 2010). Median of projected emissions estimates was calculated from output of nine modelling groups, high and low values, and 20th and 80th percentiles (used to provide ranges).

The UNEP analysis assumes that an emissions target of about 44 $GtCO_2eqGHG\ y^{-1}$ (range: 39-44) in 2020 would be needed to limit *likely* global warming to 2 degrees, though no source is provided for this target figure. Under this assumption, even the most stringent application of the Copenhagen Accord pledges leaves a gap of 5 $GtCO_2eqGHG\ y^{-1}$. A key result of the analysis is that having countries adopt their higher promised commitments (as opposed to lower ones) would reduce emissions by 2-3 $GtCO_2eqGHG\ y^{-1}$ by 2020. The biggest difference would be in Annex I countries with mitigation commitments to the ambition of the rest of the world.

There would also be additional emission reductions of 1-2 $GtCO_2eqGHG\ y^{-1}$ if countries were to move from lenient to strict rules. This would solve some of the key uncertainties in the estimates, including the carry-over of underspent emissions allowances in the Kyoto Protocol into the new targets (particularly by Russia, Ukraine and other Eastern European countries).
Two other issues remain unresolved. The first is the potential for double counting of emissions offsets, where both the provider and the buyer count them as part of their targets. Second, there are difficulties around baseline or business as usual (BAU) scenarios, for which the underlying details are often not specified. There is some evidence suggesting a tendency to make BAU scenarios high, so that emission avoidance can be larger. By one estimate, this issue could lead to an additional 1.5 $GtCO_2eqGHG\ y^{-1}$ by 2020 (Den Elzen *et al.* 2010).

6.3 Final points

We reinforce two conclusions of this report. First, we have shown that the most important aspect of near-term (2020) targets is not the emissions reductions themselves (which are likely to be modest) but their implications for later reductions. Failure to meet modest 2020 reduction targets means that much steeper reductions will be required later. The longer-term mitigation challenge can be expressed either in terms of a cumulative emissions quota or a reduction target for 2050 (Rogelj *et al.* 2010); which can be related to each other (Table S1, Section 5.2.3, Fig. 18). Even an immediate start to mitigation, with an early time of peak emissions, will require long-term mitigation rates of the order of 5% y^{-1} for many decades after the peaking time to restrict global warming to 2 degrees with 50% probability. This mitigation rate is already a major challenge. Failure to meet modest 2020 targets will make the challenge unachievable.

Second, we have highlighted the importance of the probability of success in meeting the temperature target, which has a major effect on concentration and emission goals. In broad terms, increasing the required probability of success from 50% to 80% is equivalent to lowering the temperature target by about 0.7 degrees. In terms of the available cumulative emissions to meet a warming target of 2 degrees, the same increase (50% to 80% probability of success) reduces the cumulative GHG budget by a factor of 4, from 440 to 105 GtCeqEmis (Table S1), and decreases the quota time scale from 37 years to an impossible 9 years. The combination of a 2 degree warming target with high probability of success is now unreachable.

APPENDIX A: INTERCOMPARING STUDIES ON GLOBAL WARMING AS A FUNCTION OF CUMULATIVE CO_2 EMISSIONS

Four recent papers (Allen *et al.* 2009, Meinshausen *et al.* 2009; Matthews *et al.* 2009; Zickfeld *et al.* 2009) have provided results from carbon-climate models to characterise the relationship between warming above preindustrial temperatures (ΔT) and cumulative anthropogenic CO_2 emissions (Q) from fossil fuel combustion and net land use change since the start of the industrial revolution around 1750. These results can be expressed as probability distributions for ΔT at any given Q. A fifth paper (Raupach *et al.* 2011) provides a simple analytic expression for the median peak warming.

This Appendix describes an intercomparison of results from all the above studies. This was done by fitting all results to an empirical model for the median peak warming, based on a modified power-law relationship, and a model for the probability distribution of ΔT, based on a log-normal distribution. Use of these common functional forms allows results from all studies to be standardised and intercompared.

A complicating factor in the intercomparison is that different studies used different measures for cumulative emissions Q (for example, taking emission integrals over different time periods). Therefore, the intercomparison also involved bringing the cumulative emissions Q to a common standard, here taken as the cumulative CO_2 emission from 1750 to the far future.

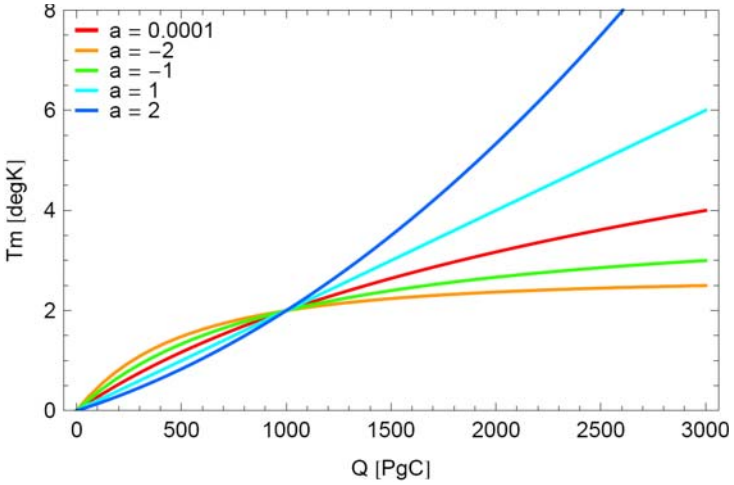


Fig. A1 Functional form for $\Delta T(Q)$ from Equation (13), with parameters ΔT_1 = 2 degC, Q_1 = 1000 GtC and values of a from −2 to 2. The red curve, with a nearly zero, approaches $\Delta T(Q)$ proportional to $\ln(1 + Q/Q_1)$. The light blue curve, with a = 1, is linear.

Functional form for peak warming

We used the following two-parameter empirical function for the peak warming $\Delta T(Q)$ resulting from cumulative emission Q:

$$\Delta T(Q) = \frac{\Delta T_1}{2^a - 1}\left(\left(\frac{Q}{Q_1} + 1\right)^a - 1\right) \qquad (13)$$

where ΔT_1 is the warming at a reference cumulative emission Q_1 (always taken as 1000 GtC), and a is a dimensionless exponent. The behaviour of Equation (13) is shown in Fig. A1.

Equation (13) has the following useful properties:

1. For all a, $\Delta T = \Delta T_1$ when $Q = Q_1$, as required by definition of ΔT_1.
2. When $a = 1$, $\Delta T(Q)$ is linear, simplifying to $\Delta T_1(Q/Q_1)$.
3. In the limit $a \to 0$, $\Delta T(Q)$ approaches logarithmic dependence on Q. In this limit, we have $\Delta T(Q) \to (1/\ln(2))\, \Delta T_1 \ln(1 + Q/Q_1)$. When $a = 0$ exactly, $\Delta T(Q)$ evaluates to 0/0 and so is undefined (in other words, there is a singularity at a=0). A small non-zero value, such as $a = 0.001$, approximates logarithmic behaviour very closely for practical purposes.
4. In the limit $Q \to 0$, $\Delta T(Q)$ approaches 0 with slope $d\Delta T/dQ \to (\Delta T_1/Q_1)a/(2^a - 1)$. This slope varies smoothly with a.
5. Negative a is valid, giving slower than logarithmic growth of $\Delta T(Q)$.
6. The exponent a determines the curvature of $\Delta T(Q)$. Summarising the foregoing properties and referring to Fig. A1, increasing Q causes $\Delta T(Q)$ to grow:
   - faster than linearly when $a > 1$;
   - linearly when $a = 1$;
   - between linearly and logarithmically when $1 > a > 0$;
   - logarithmically as $a \to 0$ (noting that $\Delta T(Q)$ is singular at a=0 exactly);
   - slower than logarithmically when $a < 0$.
7. Equation (13) is analytically invertible to give an expression for the cumulative emission Q that leads to warming ΔT:

$$Q(\Delta T) = Q_1 \left(\left(\frac{\left(2^a - 1\right)\Delta T}{\Delta T_1} + 1 \right)^{1/a} - 1 \right) \qquad (14)$$

Equation (13) is used for four reasons. First, a is a simple parameter for the curvature of $\Delta T(Q)$ (point 6). Second, the approach to logarithmic dependence of ΔT on Q (point 3) is consistent with analytic expectations in simplified conditions (Raupach *et al.* 2011). Third, Equation (13) is preferable to a simple power-law form [$\Delta T(Q) = Q_1(\Delta T/\Delta T_1)^a$] because its slope at $Q = 0$ is finite and smoothly varying with a, whereas the slope for the simple power-law form becomes infinite at $Q = 0$. Fourth, the invertibility of Equation (13) (point 7) means that the cumulative emission Q consistent with a given warming target ΔT can be found easily.

The parameter ΔT_1 in Equations (13) and (14), the warming at $Q_1 = 1000$ GtC, depends proportionally on the climate sensitivity λ (Raupach *et al.* 2011). To include this dependence, ΔT_1 is written as

$$\Delta T_1 = \Delta T_{1m}\, \lambda / \lambda_m \qquad (15)$$

where λ_m is the median climate sensitivity and ΔT_{1m} is the warming at $Q_1 = 1000$ GtC with median climate sensitivity. Several studies have estimated ΔT_{1m} as about 2 degC (see Section 5.1 and Fig. 12). Use of Equation (15) in Equations (13) and (14) allows different climate sensitivities to be incorporated.

From Equation (15), the median peak warming $\Delta T_m(Q)$ is given simply by replacing ΔT_1 withΔT_{1m} in Equation (13):

$$\Delta T_m(Q) \;=\; \frac{\Delta T_{1m}}{2^a - 1}\left(\left(\frac{Q}{Q_1} + 1\right)^a - 1\right) \qquad (16)$$

This is the warming exceeded with 50% probability, from uncertainty in climate sensitivity.

Functional form for probability distribution of climate sensitivity and peak warming

We modelled the probability distributions of climate sensitivity and peak warming by assuming that both quantities are log-normally distributed. As shown elsewhere (Raupach, paper in preparation), this assumption is in accord with recent model results on the relationship ΔT and Q (Allen *et al.* 2009, Meinshausen *et al.* 2009; Matthews *et al.* 2009; Zickfeld *et al.* 2009).

For a random variable X taking values x, the log-normal distribution has the following probability density function (PDF) and corresponding cumulative probability distribution (CDF):

$$\begin{aligned} \mathrm{PDF}_{\mathrm{LN}}(x,m,s) \;&=\; \frac{1}{s\Delta T_p\sqrt{2\pi}}\exp\left(\frac{-\ln^2(x/m)}{2s^2}\right) \\ \mathrm{CDF}_{\mathrm{LN}}(x,m,s) \;&=\; \int_0^x \mathrm{PDF}_{\mathrm{LN}}(x',m,s)\,dx' \;=\; \frac{1}{2}\left(1 + \mathrm{Erf}\left(\frac{\ln(x/m)}{s\sqrt{2}}\right)\right) \end{aligned} \qquad (17)$$

where m is the median of x and s is the spread parameter (the standard deviation of $\ln(x)$). The error function Erf(y) varies from −1 to +1 as y ranges from $-\infty$ to $+\infty$. The CDF is the probability $P_<$ that the random variable X is less than the value x. Thus, CDF(x,m,s) = $P_<$. The solution of this equation for x gives the value x of X at which the cumulative probability [prob($X < x$)] is $P_<$, or the exceedance probability [prob($X > x$)] is $P_> = 1 - P_<$. This solution is

$$x \;=\; m\exp\left(s\sqrt{2}\;\mathrm{InverseErf}\left(2P_< - 1\right)\right) \;=\; m\exp\left(s\sqrt{2}\;\mathrm{InverseErf}\left(1 - 2P_>\right)\right) \qquad (18)$$

where InverseErf(z) is the inverse error function of z = Erf(y).

Assuming a log-normal distribution of climate sensitivity implies that

$$\begin{aligned} \mathrm{PDF}(\lambda) \;&=\; \mathrm{PDF}_{\mathrm{LN}}(\lambda, \lambda_m, s) \\ \mathrm{CDF}(\lambda) \;&=\; \mathrm{CDF}_{\mathrm{LN}}(\lambda, \lambda_m, s) \end{aligned} \qquad (19)$$

Taking the median climate sensitivity as 3 degC per CO_2 doubling, with a 17-83% probability range 2 to 4.5 degC (Section 3.3), values are λ_m = 3 degC and s = 0.419119.

The PDF and CDF of peak warming are given by

$$\begin{aligned} \mathrm{PDF}(\Delta T \,|\, Q) \;&=\; \mathrm{PDF}_{\mathrm{LN}}(\Delta T, \Delta T_m(Q), s) \\ \mathrm{CDF}(\Delta T \,|\, Q) \;&=\; \mathrm{CDF}_{\mathrm{LN}}(\Delta T, \Delta T_m(Q), s) \end{aligned} \qquad (20)$$

where the median warming ΔT_m is given by Equation (16). Assuming that all uncertainty in peak warming is carried by the uncertainty in climate sensitivity, and that this is reflected by a spread parameter $s = 0.419119$ in Equation (19), this value of s also applies in Equation (20).

Fitting process and results

In the model for median peak warming (Equation (16)) and the PDF of peak warming (Equation (20)), the parameters T_{1m}, a and s were estimated by fits to results from four recent studies (Allen *et al.* 2009, Meinshausen *et al.* 2009; Matthews *et al.* 2009; Zickfeld *et al.* 2009). The process was as follows.

1. Data from all four studies were digitised.
2. Measures of Q among the different studies were standardised. The three measures among the studies were (a) total cumulative emissions from fossil fuels and land use change from preindustrial times (1750) to the far future when emissions decay to zero, in GtC (Allen *et al.* 2009; Matthews *et al.* 2009); (b) cumulative emissions over 2000-2049, in $GtCO_2$ (Meinshausen *et al.* 2009); cumulative emissions over 2001-2500, in GtC (Zickfeld *et al.* 2009). Equation (21) (Appendix B) and historic CO_2 emission data were used to calculate relationships between cumulative emissions over different time periods. These relationships (along with application of the factor of 12/44 relating $GtCO_2$ to GtC) were then used to standardise all measures of Q to measure (a), the cumulative emission from 1750 to the far future in GtC.
3. For each set of results, the parameters T_{1m}, a and s were determined by fitting Equations (16) and (20) to all available data.

The resulting parameter values are given in Table A1. Corresponding probability density functions PDF($\Delta T|Q$) forΔT are given in Fig. 19 (main text) at two values of Q. The warming ΔT (at exceedance probability $1 - P_<$), determined from Equation (18), is plotted in Fig. 20 (main text) with $P_< = 0.5$ (left panel) and 0.8 (right panel).

Table A1 Values of parameters in Equations (16) and (20). Equation (16) is the model for median warming (ΔT_m) as a function of all-time cumulative anthropogenic CO_2 emissions (Q, in GtC). Equation (20) is the model for the cumulative probability distribution CDF($\Delta T|Q$), giving the probability that the warming in response to cumulative emission Q is less than ΔT. Parameter T_{1m} is the median warming (in degC) at Q_1 = 1000 GtC; parameter a (dimensionless) determines the curvature in $\Delta T_m(Q)$; and parameter s (dimensionless) determines the spread in the assumed log-normal distribution for CDF($\Delta T|Q$).

Reference	**Notes**	**Radiative forcing**	T_{1m} **(degC)**	a	s
Allen *et al.* (2009), simple climate model	T_{1m} and a from fit to white crosses in their Fig 2; spread s from their Fig 3	CO_2 only	1.97	−0.202	0.277
Allen *et al.* (2009), C^4MIP emulations	T_{1m}, a and s from fit to coloured (C^4MIP) points in their Fig 2, taken as equal-probability ensemble members defining a distribution	CO_2 only	1.93	0.644	0.324
Zickfeld *et al.* (2009)	T_{1m}, a and s from fit their Fig 4, with Knutti06 climate sensitivity distribution	CO_2 only	1.60	1.06	0.472
Meinshausen *et al.* (2009)	T_{1m} and s from fit to their Fig 3, with default climate sensitivity distribution; a set to prior value consistent with their Fig 2	all agents	2.12	0.001	0.284
Matthews *et al.* (2009)	T_{1m}, a and s from fit to their Fig 3a, with C^4MIP members taken as equal-probability ensemble members defining a distribution	CO_2 only	1.55	1.005	0.444
Raupach *et al.* (2011)	T_{1m} and a from fit to simple equation, their Eq 8, with net nonCO_2 RF included. Value of s is estimated independently, and includes uncertainty from climate sensitivity distribution only	all agents	2.08	0.353	0.419

APPENDIX B: MATHEMATICAL FORM FOR SMOOTH CAPPED EMISSION TRAJECTORIES

The CO_2 emission flux [GtC y^{-1}] from fossil fuels and other industrial processes is specified with an analytic emissions trajectory (Raupach *et al.* 2011) defined by

$$F_{\text{Foss}}(t) = \begin{cases} \text{observations} & \text{for } t \le t_1 \\ F_m \exp\left(r\left(t - t_m\right)\right) & \text{for } t_1 < t \le t_m \\ F_m \left(1 + \left(r+m\right)\left(t-t_m\right)\right) \exp\left(-m\left(t-t_m\right)\right) & \text{for } t > t_m \end{cases} \quad (21)$$

where t_1 is the time to which observations are available, t_m is the time in the future at which which mitigation begins, F_m is the emission at time t_m, r [y^{-1}] is the proportional growth rate of $F(t)$ before mitigation, and m [y^{-1}] is an applied mitigation rate. This "smooth capped" emissions trajectory merges an exponential growth phase with growth rate r, applicable for $t \le t_m$, with a mitigation phase starting at $t = t_m$ in which emissions ultimately decrease exponentially at a mitigation rate m. Emissions reach their maximum after $t = t_m$ because initial growth must be overcome. The all-time cumulative emission [GtC] is the finite quantity

$$\begin{aligned} Q_{\text{Foss}}(\infty) &= \int_{t_0}^{\infty} F_{\text{Foss}}(t)\, dt \\ &= Q_{\text{Foss}}(t_1) + \frac{F_m}{r}\left(1 - \exp\left(r\left(t_1 - t_m\right)\right)\right) + \frac{F_m\left(2m+r\right)}{m^2} \end{aligned} \quad (22)$$

where the three terms on the right hand side are respectively the contributions to the integral from the past ($t \le t_1$), future pre-mitigation ($t_1 < t \le t_m$) and mitigation ($t > t_m$) phases of Equation (21).

Table B1 summarises several mathematical properties of the emissions trajectory defined by Equation (21).

Table B1 Summary of mathematical properties of the smooth capped emissions trajectory, Equation (21)., for times t after the start of mitigation ($t > t_m$).

Emissions trajectory as a function of time t from start of mitigation at $t = t_m$	$F(t) = F_m\left(1 + (r+m)(t-t_m)\right)\exp\left(-m(t-t_m)\right)$
Cumulative emission from time $t = t_m$ to $t = \infty$	$Q_m = F_m\left(\frac{2m+r}{m^2}\right)$
Mitigation rate needed to meet quota Q_m from $t = t_m$ to $t = \infty$	$m(Q_m) = \left(F_m + \sqrt{F_m(F_m + rQ_m)}\right)\Big/ Q_m$
First derivative	$F'(t) = F_m\left(r - (r+m)m(t-t_m)\right)\exp\left(-m(t-t_m)\right)$
Second derivative	$F''(t) = F_m m\left(-m-2r+(r+m)m(t-t_m)\right)\exp\left(-m(t-t_m)\right)$
Proportional growth rate (PGR)	$\mathrm{PGR}(t) = \frac{F'(t)}{F(t)} = \frac{m+r}{1+(m+r)(t-t_m)} - m$
Time of maximum emissions (when $F'(t_{\mathrm{Max}}) = 0$)	$t_{\mathrm{Max}} = t_m + \frac{r}{m(m+r)}$
Time of maximum emissions decline (inflection point, when $F''(t_{\mathrm{Inf}}) = 0$)	$t_{\mathrm{Inf}} = t_m + \frac{m+2r}{m(m+r)}$
Time at which emissions return to initial emissions: $F(t_{1.0}) = F_m$	$t_{1.0} \approx t_m + \frac{m^2+3mr+4r^2-m(m+r)\exp\left(2r/(m+r)\right)}{mr(m+r)}$ (First Newton iteration from initial estimate $t_{1.0} \approx 2t_{\mathrm{Max}}$, with typical error 1-2% overestimation)
Time at which emissions fall to half of initial emissions: $F(t_{0.5}) = 0.5F_m$	$t_{0.5} \approx t_m + \frac{4r + m\left[3 - \exp\left((m+2r)/(m+r)\right)/2\right]}{m(m+r)}$ (First Newton iteration from initial estimate $t_{0.5} \approx t_{\mathrm{Inf}}$, with typical error 1-2% overestimation)

APPENDIX C: AGGREGATE CUMULATIVE EMISSION QUOTAS FOR MULTIPLE GASES

The relationship between warming (ΔT) and cumulative emissions (Q) depends on the climate sensitivity, which in turn depends on the assumed probability $P_<$ for staying below the warming ΔT, the "chance of success". The approach in this report is to calculate $Q(\Delta T, P_<)$ for given values of warming (ΔT) and chance of success ($P_<$).

CO_2-only world

The process for calculating $Q(\Delta T, P_<)$ (in GtC) proceeds in three simple steps:

1. The climate sensitivity corresponding to $P_<$ is calculated from Equation (18), with median $\lambda_m = 3$ degC and spread $s = 0.419119$ (Appendix A).
2. This climate sensitivity is used to calculate ΔT_1 from Equation (15).
3. This ΔT_1 is used in the inverse of the model for $\Delta T(Q)$, Equation (14), to calculate Q.

World with radiative forcing from multiple agents

With radiative forcing from multiple agents (CO_2, non-CO_2 GHGs and non-gaseous agents including aerosols), the situation is more complicated. We seek the cumulative emissions of all Kyoto gases (CO_2 and non-CO_2), given by Equation (12) in the main text and quantified in carbon emission equivalents (GtCeqEmis). This is obtained here by the following steps, some of which include major assumptions.

Procedure

1. The warming due to GHGs only (ΔT_{GHG}) is determined as:

$$\begin{aligned} \Delta T_{GHG} &= \Delta T - \Delta T_{Other} \\ &= \Delta T - \lambda RF_{Other} \end{aligned} \qquad (23)$$

   In this equation, the warming from agents other than long-lived GHGs (aerosols, ozone etc.) has been expressed in terms of the corresponding radiative forcing, RF_{Other}, using the climate sensitivity. Because RF_{Other} is negative, ΔT_{GHG} is larger than ΔT.

   The required value RF_{Other} is at the time of peak temperature or stabilisation, not at the present time. In calculations accompanying this report, we use a fixed value $RF_{Other} = -0.3$ W m^{-2}, typical of the radiative forcing from aerosols, ozone etc.in the later part of this century (2070-2100) according to Representative Concentration Pathways (RCPs). This is the centre of a plausible range for RF_{Other} of −0.1 to −0.5 W m^{-2} (see Fig. 10).

2. As in a CO_2-only world, the climate sensitivity corresponding to the prescribed chance of success ($P_<$) is calculated from Equation (18), with $\lambda_m = 3$ degC and $s = 0.419119$.
3. Q_{GHG} is calculated from Equation (14), replacing ΔT with the warming ΔT_{GHG} due to Kyoto gases from Equation (23). Using Equation (15), the expression for Q_{GHG} is:

$$Q_{\mathrm{GHG}}\left(\Delta T\right) \;=\; Q_{1}\left(\left(\frac{\left(2^{a}-1\right)\left(\Delta T-\lambda\,\mathrm{RF}_{\mathrm{Other}}\right)}{\left(\lambda/\lambda_{m}\right)\Delta T_{1m}}\;+\;1\right)^{1/a}\;-\;1\right) \qquad (24)$$

Assumptions

There are two main assumptions embodied in Equation (24).
First, it is assumed that the relationship between ΔT and Q carries over from a CO_2-only world to a world with radiative forcing from multiple agents, provided Q is expressed in carbon emission equivalents (GtCeqEmis) using Equation (12). This amounts to taking literally the concept of carbon emission equivalents as the weighted emission of multiple gases which would give the same warming as the equivalent emission of pure CO_2. Here, the weights are assumed to be 100-year Global Warming Potentials (GWPs); see Section 5.3. Scientific difficulties with GWPs are well known (eg Fuglestvedt *et al.* 2003; Shine *et al.* 2003; Shine *et al.* 2005). These stem partly from the fact that GWPs depend strongly on the selected time horizon.

Second, it is assumed that the contribution to warming from "other" agents, mainly aerosols, can be deducted from the warming target as in Equation (23), using a single representative $\mathrm{RF}_{\mathrm{Other}} = -0.3$ W m^{-2} (range −0.1 to −0.5). This assumption is rough, but it needs to be considered along with many other assumptions about the treatment of radiative forcing from non-gaseous agents that are embedded not only in this report but also in all treatments of climate change based on globally aggregated radiative forcings as in Equation (1). These approximations together contribute to a large uncertainty in estimates of present $\mathrm{RF}_{\mathrm{Other}}$, particularly from aerosols (see Section 3.2.3). Present contributions due to anthropogenic aerosols are −0.5 (range −0.9 to −0.1) W m^{-2} for the direct radiative effect and −0.7 W m^{-2} (range −1.8 to −0.3) for the indirect (cloud) effects (ranges are 90% confidence intervals).

APPENDIX D: GUIDE TO CLIMATE GOALS CONVERSION TABLE

The Excel workbook "ClimateGoalsConversionTable.V01.xls" (Version 1) provides a simple means of converting between climate goals expressed in terms of temperature targets, concentration targets, radiative forcing, and cumulative emissions.

The algorithms are simple and in some cases approximate, especially where highlighted below.

The workbook contains five sheets:

- "Notes" – these notes;
- "Versions" – version history;
- "ClimateGoals" – conversions between temperature targets, concentration targets in several forms of CO_2 equivalents, radiative forcing, and cumulative emissions of CO_2 (the "carbon budget") and of all greenhouse gases (GHGs) (the "GHG budget");
- "CarbonBudget" – properties of carbon budgets at specified cumulative CO_2 emissions and years for starting mitigation, including the year of peak emissions, the required exponential emissions decline rate after the peak to meet the allocated carbon budget, and emissions in 2020 and 2050 as percentages of emissions in 1990;
- "GHGBudget" – similar properties for cumulative emissions budgets for all GHGs;
- "Parameters" – all parameters used in the calculations (for most purposes, it should not be necessary to change any entries in this sheet).

Cells entries are colour coded as follows:

- **red** entries are values entered by the user;
- **black** entries are computed (these cells should not be changed);
- **blue** entries are reference parameter values to guide selections in sheet "Parameters". These cells should not be changed.

The main algorithms can be summarised as follows. References to the body of the report are given in square brackets.

1. The median climate sensitivity is taken as 3 degC per CO_2 doubling, with a 67% probability of falling between 2 and 4.5 degC (IPCC 2007a) [Section 3.3].

2. Uncertainty in climate sensitivity is assumed to be log-normally distributed [Appendix A, Equations (17), (18)]. This uncertainty in climate sensitivity is propagated into all climate goals as a high-level parameterisation of all uncertainties in the climate system.

3. Total radiative forcing from all agents (CO_2, non-CO_2 gases, and non-gaseous agents including aerosols) is calculated from the temperature goal using the climate sensitivity [Equation (7)].

4. Total radiative forcing from all agents is converted to a CO_2 equivalent concentration CO_2eqTot [Equation (5)].

5. Radiative forcing from GHGs (CO_2, long-lived non-CO_2 gases) is calculated from total radiative forcing by assuming that the radiative forcing contribution from aerosols and other non-gas agents is -0.3 W/m^2 at climate stabilisation, on the basis of RCP results [Appendix C]. This figure is adjustable in sheet "Parameters".

6. The radiative forcing from GHGs is converted to a CO_2 equivalent concentration CO_2eqGHG [Equation (5)].

7. The contribution of CO_2 only is calculated ***approximately*** from the concentration CO_2eqGHG, by assuming that the radiative-forcing contribution of CO_2 is a constant fraction of the radiative forcing from all GHGs (including non-CO_2 GHGs but excluding non-gaseous agents such as aerosols). This fraction is adjustable in sheet "Parameters".

8. Cumulative CO_2 emissions ("carbon budgets") for specified temperature targets are calculated with a simple modified power-law equation [Equation (14); Appendices A and C].

9. Cumulative GHG emissions for all long-lived GHGs ("GHG budgets") are calculated ***approximately*** by adding a small temperature increment to the temperature used to calculate the carbon budget, to account for the small cooling effect of aerosols at climate stabilisation. The resulting GHG budget is assumed to be expressed in carbon equivalent emissions (GtCeqEmis) using 100-year Global Warming Potentials to bring emissions of different gases to a single measure [Section 5.3, Equation (24), Appendix C].

10. Properties of cumulative emissions trajectories, such as the year of peak warming and the emissions in 2020 and 2050, are calculated using an analytic form for a cumulatively capped emissions trajectory (Raupach *et al.* 2011). These properties depend on both the assumed cumulative cap (carbon budget or GHG budget) and also on the assumed year for starting mitigation [Section 5.2 and Appendix B].

ACKNOWLEDGMENTS

This work was commissioned by the Department of Climate Change and Energy Efficiency, Australian Government. We are grateful for comments on a draft of this report from Dr John Church and Dr Steve Hatfield-Dodds.

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The Centre for Australian Weather and Climate Research is a partnership between CSIRO and the Bureau of Meteorology.