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Keeping warming within the 2 °C limit after Copenhagen

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ABSTRACT

The object of the United Nations Climate Change Conference in Copenhagen in December 2009 was to reach an agreement on a new international legal architecture for addressing anthropogenic climate change post-2012. It failed in this endeavour, producing a political agreement in the form of the Copenhagen Accord. The Accord sets an ambitious goal of holding the increase in the global average surface temperature to below 2 °C. This paper describes 45 CO_2-only mitigation scenarios that provide an indication of what would need to be done to stay within the 2 °C limit if the international climate negotiations stay on their current path. The results suggest that if developed countries adopt a combined target for 2020 of $\leq$20% below 1990 levels, global CO_2 emissions would probably have to be reduced by $\geq$5%/yr, and possibly $\geq$10%/yr, post-2030 (after a decade transitional period) in order to keep warming to 2 °C. If aggressive abatement commitments for 2020 are not forthcoming from all the major emitting countries, the likelihood of warming being kept within the 2 °C limit is diminutive.

1. Introduction

The object of the United Nations Climate Change Conference in Copenhagen in December 2009 was to reach agreement on a new international legal architecture for addressing anthropogenic climate change post-2012. It failed in this endeavour, producing a political agreement in the form of the Copenhagen Accord. The Accord establishes a broad mitigation framework based on the 'schedules approach' originally put forward by Australia, under which countries undertake to implement or meet specific mitigation commitments or targets that are registered in schedules.[1] In keeping with this framework, developed countries have committed to submit quantified economy-wide targets for 2020 by 31 January 2010. Participating developing countries have agreed to put forward nationally appropriate mitigation actions by the same date. The targets and commitments that are lodged by developed and developing countries will be registered in schedules. Controversially, the Accord contains no long-term global goal for emissions reductions as envisaged under the Bali Action Plan that was formulated in 2007.[2] However, it does embrace an objective of keeping the increase in the global average surface temperature below 2 °C (presumably from pre-industrial levels) and signatories to the Accord have committed to 'take action to meet this objective consistent with science and on the basis of equity'.[3]

The nature of the negotiations at, and outcome from, the Copenhagen Conference suggests that there is likely to be ongoing uncertainty about a number of key mitigation issues, especially what commitments will be adopted for 2020 and the extent to which these commitments will be met. The success of the international community in constraining emissions over the next decade will largely determine whether it is possible to keep warming to 2 °C. The aim of this paper is to analyse how different emissions trajectories to 2020 could affect the capacity to meet the Copenhagen Accord's 2 °C temperature target. To do this, 45 simplified CO_2-only mitigation scenarios are developed to show what would have to be done after 2020 to stay within the 2 °C limit if the international climate negotiations stay on their current path. The results suggest that meeting the 2 °C target is an arduous task and that, without a significant increase in the mitigation commitments of all major emitting countries, the chances of meeting it are diminutive.

The paper is set out as follows: Section 2 provides details of current developed and developing country mitigation pledges. Section 3 describes the method that was used to develop the mitigation scenarios. The results are presented in Section 4. Section 5 discusses the implications of the results and Section 6 provides a conclusion.

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[1] FCCC/AWGLCA/2008/Misc.5/Add.2 (Part I), FCCC/KP/AWG/2009/MISC.6.Add.2, and FCCC/KP/AWG/2009/MISC.8.

[2] UNFCCC, Decision 1/CP.13 (FCCC/CP/2007/6/Add.1).

[3] Copenhagen Accord, cl. 2 (available at: http://unfccc.int/files/meetings/cop_15/application/pdf/cop15_cph_auv.pdf (21 December 2009)).

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Table 1
Likely developed country CO2-e emissions targets for 2020, as at 1 January 2010.
Source: UNFCCC (2009a; 2009b); White House (2009); AOSIS (2009); Australian Department of Climate Change (2009a).

Country[a]	Low range		High range		Inclusion of LULUCF
	Target	$MtCO_2$-e	Target	$MtCO_2$-e	
Australia	−5% on 2000	525	−25% on 2000	415	Yes
Belarus	−5% on 1990	123	−10% on 1990	116	Yes
Canada	−20% on 2006	575	−20% on 2006	575	Yes
Croatia	+6% on 1990	33	+6% on 1990	33	Yes
European Union (EU-27)	−20% on 1990	4451	−30% on 1990	3895	No for -20%, Yes for 30%
Iceland	−15% on 1990	3	−15% on 1990	3	Yes
Japan	−15% on 2005	1154	−25% on 1990	1018	Yes
Kazakhstan	−15% on 1992	269	−15% on 1992	269	TBD
Liechtenstein	−20% on 1990	0.2	−30% on 1990	0.2	No
Monaco	−20% on 1990	0.1	−20% on 1990	0.1	No
New Zealand	−10% on 1990	56	−20% on 1990	49	Yes
Norway	−30% on 1990	35	−40% on 1990	30	Yes
Russia[b]	−10% on 1990	2987	−25% on 1990	2489	Yes
Switzerland	−20% on 1990	42	−30% on 1990	37	Yes
Ukraine	−20% on 1990	741	−20% on 1990	741	TBD
United States	−17% on 2005	5878	−17% on 2005	5878	Yes
Aggregate at 2020		17225		15901	
Aggregate in 1990					
Ex LULUCF			18808		
Incl LULUCF			17459		

[a] Turkey was excluded due to lack of information.
[b] Russia announced a target of 20–25% below 1990 levels at the EU-Russia Summit in November 2009. However, at the Copenhagen Conference, the Russian delegation stated that this target range was aspirational only (AOSIS, 2009). On account of this, the low end of its previous pledge (i.e. 10% below 1990) was used here.

2. Mitigation commitments for 2020

Developed countries are defined here as Annex I countries under the UNFCCC, including Turkey and Belarus, plus Cyprus, Malta and Kazakhstan.[4] A number of other industrialised countries may ultimately adopt emission limitation targets for 2020. However, due to the uncertainty surrounding which countries may be included and to promote simplicity, these countries are classified as developing counties (or non-Annex I countries) for these purposes. This is consistent with the Copenhagen Accord, which maintains the Annex I/non-Annex I distinction.

Table 1 contains details of the 2020 abatement pledges made by developed countries in the lead up to, and at, the Copenhagen Conference. The pledges were converted into CO_2-e using data published by the UNFCCC Secretariat (UNFCCC, 2009a) and information released by individual countries (Australian Department of Climate Change, 2009a; EEA, 2009; U.S. EPA, 2009a; U.S. EPA, 2009b). High- and low-range abatement estimates are provided to account for the nature of the pledges. In particular, a number of countries have announced a range of possible abatement targets, with higher targets being conditional on other developed and developing countries adopting strong abatement commitments. Aggregating and comparing the targets that have been put forward are difficult because of the vague nature of some pledges, use of different base years and varying approaches to land use, land use change and forestry (LULUCF). Notwithstanding this, if the sum of the 2020 targets is compared to gross developed country emissions (i.e. excluding LULUCF) in 1990, the aggregate percentage reduction is between 10% and 17%. The equivalent range for net developed country emissions (i.e. including LULUCF) is 9–14%.[5] Due to the nature of the pledges, these estimates are subject to a degree of uncertainty. However, they are similar to those from a number of other studies (Rogelj et al., 2009; Levin and Bradley, 2009; Ecofys and Climate Analytics, 2009; Netherlands Environmental Assessment Agency, 2009; AOSIS, 2009).

Based on current pledges, the aggregate developed country abatement target for 2020 is likely to be significantly below the much quoted 25–40% range that was included in Working Group III's contribution to the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) (Metz et al., 2007). This range was adopted at the Bali Climate Change Conference in 2007 as a starting point for negotiations on developed country abatement targets and was cited in the final Bali Action Plan. It reflects Working Group III's survey of the literature on what abatement contribution developed countries should make if the world agrees to pursue a mitigation strategy that would stabilise the atmospheric concentration of greenhouse gases at 450 ppm CO_2-e. The range partially reflects uncertainties in climate science, particularly those associated with climate sensitivity and climate–carbon cycle feedbacks. It is also a product

[4] Neither Turkey nor Belarus currently has binding emission limitation commitments under the Kyoto Protocol. The Conference of the Parties agreed to include Malta in Annex I at the Copenhagen Conference. However, Annex I will not be formally amended to include Malta until the procedures outlined in Articles 15 and 16 of the Convention have been satisfied. Kazakhstan is an Annex I country for the purposes of the Kyoto Protocol but is a non-Annex I country under the UNFCCC. Cyprus was included as a developed country for current purposes on the basis that it is a member of the European Union (EU) and is covered by the EU-27 mitigation target for 2020.

[5] This estimate assumes that current LULUCF rules are maintained through to 2020 and it accounts for potential sources and sinks in 'excluded' LULUCF activities (i.e. for countries whose pledged target does not include LULUCF, the excluded activities are all LULUCF activities; for other countries they are confined to activities not elected under Article 3.4 of the Kyoto Protocol). Likely emissions/sinks in excluded LULUCF sectors were projected using the average over the period 1990–2007 (UNFCCC, 2009). For the United States, it was assumed that offset LULUCF credits are only granted for projects that result in additional abatement. Net emissions for the United States in 2020 were then calculated as the gross target less the likely removals from LULUCF under business-as-usual (BAU) conditions. BAU LULUCF projections for the United States for 2020 were obtained from U.S. Department of State (2007).

Table 2
Developing country mitigation pledges, as at 1 January 2010.
Source: Fransen (2009), Stern (2009) and Hussain (2009).

Country	Mitigation pledge[a]
China	40–45% reduction in emission intensity of Chinese economy by 2020 on 2005 levels.
India	20–25% reduction in emission intensity of Indian economy by 2020 on 2005 levels.
Malaysia	Up to 40% reduction in emission intensity of Malaysian economy by 2020 on 2005 levels.
Brazil	36–39% reduction in emissions below BAU by 2020.
Indonesia	26–41% reduction in emissions below BAU by 2020.
South Africa	34% reduction in emissions below BAU by 2020.
South Korea	30% reduction in emissions below BAU by 2020 (or 4% below 2005 levels by 2020).

[a] BAU refers to business-as-usual.

of value judgements about what constitutes an equitable division of the abatement burden between developed and developing countries. Lower abatement targets for developed countries for 2020 means developing countries must do more if a 450 ppm CO_2-e goal is going to be achieved and *vice versa* (den Elzen and Höhne, 2008).

Failure of the developed countries to agree to cut emissions by between 25% and 40% by 2020 will have two deleterious effects on the chances of staying within the 2 °C limit. Firstly, it will directly slow the rate of abatement. Secondly, it will decrease the likelihood of developing countries adopting and implementing material abatement commitments in the short- to medium-term.[6] At the time of writing, a number of major developing countries had made mitigation pledges. Details of some of these are provided in Table 2. If developed countries adopt 2020 mitigation targets that are below the 25–40% range, developing countries may back away from meaningful mitigation commitments. Their resolve to implement any commitments they do put forward could also be adversely affected. The reverse is also true—developed country mitigation targets are influenced by the positioning of developing countries. The jostling between developed and developing countries over abatement commitments is similar to a prisoner's dilemma, where the pursuit of self-interest by participating parties could ultimately produce a sub-optimal outcome.

In the remainder of the paper, simplified CO_2-only emissions mitigation scenarios are constructed to illustrate the importance of developed and developing country abatement commitments and show what would have to be done post-2020 to stay within the 2 °C limit if there is not a meaningful shift in the direction of international negotiations.

3. Emissions mitigation scenarios–method

3.1. Introduction

Forty-five emissions mitigation scenarios were developed for the above purposes. These mitigation scenarios were developed using a 'CO_2-plus' approach, where CO_2 emissions scenarios were developed in isolation and a non-CO_2 component (i.e. the net effect of non-CO_2 greenhouse gases and other pollutants) was added to estimate the net anthropogenic influence on the climate. The CO_2-plus approach is an easy and transparent way of analysing the relationship between CO_2 and non-CO_2 gases in mitigation pathways. The non-CO_2 component can be held constant across all scenarios—i.e. a single set of non-CO_2 emissions, atmospheric concentrations or radiative forcing assumptions can be added to the CO_2 scenarios. Alternatively, the non-CO_2 component can vary across the CO_2 scenarios to account for the relationship between gases and the fact that some non-CO_2 emissions are likely to fall as CO_2 emissions are reduced (e.g. mitigation of CO_2 is likely to result in a reduction in SO_2 emissions) (Meinshausen et al., 2006). In this case, three sets of non-CO_2 assumptions were used in developing the 45 scenarios, the details of which are provided below.

The decision to adopt the CO_2-plus approach was based on the desire for simplicity and transparency and the difficulty in developing accurate future estimates of the ratio between CO_2/non-CO_2 emissions and forcings (Meinshausen et al., 2006; Allen et al., 2009; Wigley et al., 2009). More complex methods use an integrated approach where marginal abatement cost curves of relevant gases are used to find a least cost multi-gas abatement solution to a given climate or emission objective. The benefit of these approaches is their capacity to provide insights into the relationship between gases and the costs associated with the available mitigation options. The downside is their complexity. It is also arguable that the assumption that governments and polluters will respond rationally and pursue least cost abatement strategies for all gases simultaneously is unrealistic and does not reflect actual behaviour.

In developing the scenarios, CO_2 emissions were broken into their two sources: fossil emissions (i.e. emissions from fossil fuel combustion, cement manufacture and gas flaring) and emissions from land use change and forestry (LUCF).[7] Estimates of LUCF emissions are subject to a wide range of uncertainty (Denman et al., 2007). This creates difficulties when developing scenarios and projecting future climate changes. Not only does the uncertainty complicate the process of projecting LUCF emissions but it also hinders the capacity to measure the historic, and project the future, residual land sink (i.e. the CO_2 removals from undisturbed terrestrial ecosystems). This element of uncertainty should be kept in mind when interpreting the results of these and other scenarios.

3.2. Method overview

The scenarios were developed using a four-step approach.

Step 1—Three cumulative CO_2 emissions 'budgets' for the 21st century were calculated on the basis of different non-CO_2 emissions and carbon-cycle assumptions.

Step 2—CO_2 emissions estimates were derived for the period 2001–2010.

Step 3—With regard to the current state of international climate negotiations, CO_2 emissions were projected for the period 2011–2020.

Step 4—Global emissions were assumed to peak at or before 2020 in all scenarios. From 2021, it was assumed that global emissions decline at an increasing rate, before reaching a maximum rate of decay in 2030. From 2030 to 2100, it was assumed that global emissions continue to decline at the maximum rate while staying within the relevant 21st century emissions budget.

[6] The willingness of developing countries to adopt and implement meaningful abatement commitments is also influenced by the positioning of developed countries on other issues such as financing and technology transfers. For simplicity, this paper focuses on mitigation commitments.

[7] For the purposes of this study, peatland emissions were excluded from LUCF estimates. This was due to measurement uncertainty (van der Werf et al., 2009) and the desire to ensure comparability with other similar studies (Weyant et al., 2006; Anderson and Bows, 2008; Garnaut, 2008).

Appendix A lists the 45 scenarios and associated key assumptions. There are five scenario 'families'– COPENA10, A15, A20, A30 and A40—that reflect the assumed actual percentage reduction in net developed country CO_2 emissions in 2020 below 1990 levels (e.g. under COPENA10, developed country CO_2 emissions are 10% below 1990 levels in 2020). It is assumed for these purposes that CO_2 emissions are reduced in proportion to the total developed country CO_2-e emission target for the six Kyoto gases (i.e. CO_2, CH4, N2O, HFCs, PFCs and SF6).

In each scenario family, there are nine scenarios. The 'scenario number'—(1)560, (3)560 etc.—is determined by the assumptions regarding developing country fossil CO_2 emission trends to 2020 and cumulative global CO_2 emissions for the period 2001–2100. The number in brackets (i.e. 1, 3 or 5) is the assumed annual rate of developing country fossil CO_2 emissions growth between 2010 and 2020 (i.e. (1) corresponds to 1%/yr growth). The number after the brackets is the assumed cumulative global CO_2 emissions for the 21st century—560, 430 and 360 GtC.

3.3. Step 1: Cumulative 21st century CO_2 emissions

Building on the work of the likes of Allen et al. (2009), Matthews et al. (2009), Anderson and Bows (2008), Broecker (2007), and Wigley et al. (1996), a cumulative emission approach (or budget approach) was adopted to develop the scenarios. As Allen et al. (2009) and Matthews et al. (2009) explain, the projected CO_2-related temperature response is insensitive to the timing of CO_2 emissions. Provided emissions follow a relatively smooth trajectory whereby they peak at a given date and then head into exponential decline, cumulative CO_2 emissions over time can be used to determine the likely amount of CO_2-induced warming (what Allen et al. (2009) refer to as the 'Cumulative Warming Commitment' (CWC)).

Cumulative CO_2 emissions 'budgets' can also be determined for particular CO_2 atmospheric concentration stabilisation objectives. The idea of using budgets for these purposes is complicated by the fact that the concentration profile that is followed to reach the stabilisation objective affects the size of the emission budget. The extent to which alternative profiles affect the size of the associated budget depends on the nature of the profiles and the budget period. Jones et al. (2006, p. 604) suggest emissions budgets to stabilisation 'may be relatively insensitive to the chosen pathway'. Yet budgets that are set for an arbitrary period can be significantly affected by the profile. Further, the emission budget for an overshoot profile can be significantly different from the budget associated with a direct stabilisation profile. Despite this issue, emissions budgets provide a useful way to compare the magnitude of the abatement task associated with different policy objectives.

Three cumulative CO_2 emission budgets for the period 2001–2100 were developed to account for different carbon-cycle and non-CO_2 assumptions: 560, 430 and 360 GtC. The 560 GtC budget was drawn from Allen et al. (2009), where cumulative emissions of 1TtC were used for the period 1750–2500 for a 2 °C CWC.[8] Approximately 440 GtC were emitted between 1750 and 2000, leaving 560 GtC for the period to 2500. For current purposes, it was assumed that the total 560 GtC is emitted over the period 2001–2100. That is, the question posed was by how much do global CO_2 emissions have to be reduced post-2020 in order to avoid exceeding the threshold for warming of 2 °C from CO_2-only in the 21st century? This budget assumes the net effect of non-CO_2 climate forcing agents is negligible, which is unrealistic. A negligible contribution to warming from non-CO_2 gases would only arise if the warming effect of non-CO_2 greenhouse gases was nullified by the negative forcing associated with cooling agents. This is theoretically possible but unlikely without geo-engineering (e.g. stratospheric sulphur injections (Crutzen, 2006)). Most mitigation studies indicate that non-CO_2 radiative forcing is likely to be positive in the late 21st century in risk averse mitigation scenarios (i.e. ≤ 550 ppm CO_2-e), typically adding in the order of 20–40% to CO_2-only forcing (Leggett et al., 1992; Wigley, 1995; Wigley et al., 1996; Meinshausen et al., 2006; Weyant et al., 2006; Fisher et al, 2007; Garnaut, 2008). Due to the exclusion of the possibility of significant positive forcing from non-CO_2 agents, the 560 GtC budget effectively provides an 'outer marker' of the abatement that is necessary to stay within the 2 °C limit.

The 430 GtC budget was used to approximate the CO_2-only emissions over the 21st century under an optimal (or least cost) multi-gas abatement scenario that leads to stabilisation of the atmospheric concentration of greenhouse gases at 450 ppm CO_2-e in or around 2150. The choice of emissions budget was informed by the Garnaut Climate Change Review's 450 ppm CO_2-e stabilisation scenario (Garnaut, 2008). As with other similar 450 ppm CO_2-e stabilisation scenarios, the Garnaut scenario is believed to provide a ~50% chance of exceeding the 2 °C limit. Under the Garnaut scenario, the atmospheric concentration of CO_2-e stabilises at 450 ppm around 2150. The concentration of CO_2 peaks in around 2050 at 440 ppm, and by 2100 is brought back to 404 ppm, which is partly due to the fact that the scenario assumes small negative CO_2 emissions in the final decade of the century. The Garnaut scenario has the global average surface temperature peaking at around ~2 °C in the latter part of the 21st century. The cumulative CO_2 emissions over the 21st century under this scenario are 404 GtC with the negative emissions included and 410 GtC without.

To derive the 430 GtC budget, a simple climate model (MAGICC, version 5.3.v2 (Wigley, 2009)) was used in conjunction with the scenario assumptions outlined in Steps 2, 3 and 4 below to mimic key markers of the Garnaut scenario's CO_2 concentration profile. The markers were the atmospheric CO_2 concentration peak at ~440 ppm in or around the middle of the century and a concentration at the end of the 21st century of ~405 ppm. Consistent with the Garnaut scenario, climate sensitivity was set at 3 °C and MAGICC's mid-range climate–carbon cycle feedback setting was applied. An iterative approach then was adopted in which the cumulative CO_2 emissions were adjusted under the scenario assumptions outlined below until the concentration profile markers were achieved. The resulting cumulative CO_2 emissions for the 21st century were approximately 430 GtC. This provides a conservative estimate of the allowable cumulative CO_2 emissions for the 21st century if the object is to stay within the 2 °C limit by stabilising the atmospheric concentration of greenhouse gases at ~450 ppm CO_2-e in the early- to mid-2100s.

The CO_2 concentration profiles from the scenarios that use the 430 GtC budget are shown in Fig. 1. The notable difference to the profile from the Garnaut 450 ppm CO_2-e scenario is the earlier peak in the atmospheric CO_2 concentration, which occurs around 2040 rather than 2050. This is attributable to two factors. Firstly, the scenarios here assume that there are no negative CO_2 emissions in the 21st century. Secondly, the scenarios here have significantly higher estimates of CO_2 emissions from land use change and forestry (LUCF) in the earlier part of the 21st century and, consequently, higher total CO_2 emission estimates. For example, the scenarios here assume LUCF emissions in 2005 of 5.4 $GtCO_2$, with total global CO_2 emissions of 34.6 $GtCO_2$, consistent with Boden et al. (2009), Marland and Boden (2009)

[8] This is significantly higher than the estimate in Matthews et al. (2009). The lower estimate was chosen because of its consistency with a precautionary approach to climate policy making, as required under Article 3 of the UNFCCC.

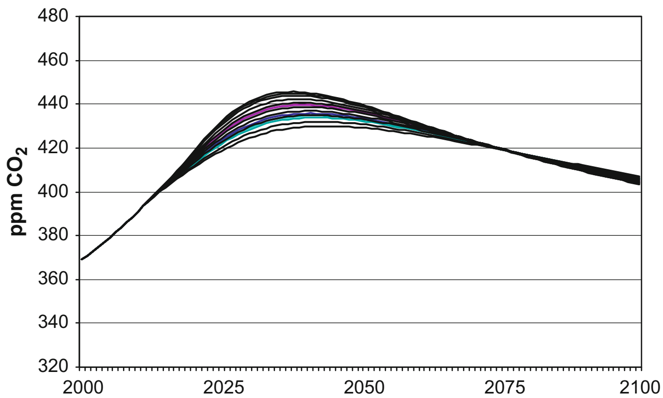

Fig. 1. Atmospheric concentration of CO2 under scenarios with cumulative 21st century emissions of 430 GtC.

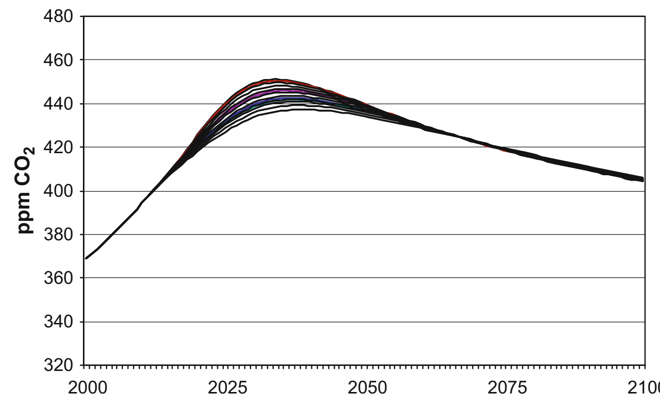

Fig. 2. Atmospheric concentration of CO2 under scenarios with cumulative 21st century emissions of 360 GtC.

and Houghton (2008). For the same year, the Garnaut scenario has LUCF estimates of 2.8 $GtCO_2$ and total CO_2 emissions at 31.1 $GtCO_2$ (Garnaut, 2008; Australian Department of Treasury, 2008).

The scenarios that were developed with the 430 GtC budget correspond neatly with the results from Meinshausen et al. (2009), where it was found that multi-gas mitigation scenarios with cumulative CO_2 emissions over the period 2000–2049 of 1437 $GtCO_2$ (392 GtC) have a ~50% chance of exceeding the 2 °C limit. All the 430 GtC scenarios here have cumulative CO_2 emissions over the first half of the 21st century of between 360 and 400 GtC. While consistent with Meinshausen et al. (2009), the 430 GtC budget for the 21st century is higher than what is assumed in many other scenarios that aim to keep temperatures below 2 °C. The IPCC AR4 found that scenarios aiming for targets $\leq$3 W/m2 above pre-industrial levels (i.e. 445–490 ppm CO_2-e) 'generally' have 21st century CO_2 budgets of ~300 GtC, with a range of between 218 and 409 GtC (Fisher et al., 2007, pp. 198–199). Similarly, the German Advisory Council on Global Change has argued that cumulative CO_2 emissions during the first half of the 21st century should be kept to ~300 GtC in order to give a 67% chance of keeping warming below 2 °C (WBGU, 2009).[9] The available evidence suggests that, if there is a desire to adopt a precautionary approach to the 2 °C limit, policy makers should ensure that cumulative CO_2 emissions over the 21st century are significantly less than 430 GtC.

The 360 GtC budget is designed to reflect the risk that climate–carbon cycle feedbacks respond earlier and more strongly than previously believed, resulting in a greater accumulation of CO_2 in the atmosphere in the first two decades of the 21st century. As a result, greater CO_2 emissions reductions will be necessary post-2020 to keep the atmospheric concentration of CO_2 to levels consistent with the 2 °C limit. To illustrate the nature of this risk, and how it could affect the required rate of abatement post-2020, MAGICC was used under the high carbon-cycle settings to generate a CO_2 concentration profile that is consistent with a sub-2 °C outcome under the current 'best guess' climate sensitivity assumptions (i.e. $2 \times CO_2 = 3$ °C). To generate the profile, an iterative approach was used whereby the cumulative CO_2 emissions for the 21st century were varied under the scenario assumptions outlined below and fed through MAGICC until the atmospheric concentration of CO_2 in 2100 was ~405 ppm (i.e. similar to the concentration at 2100 under the Garnaut scenario). This method generated cumulative emissions for the 21st century of 360 GtC.

[9] See also Weaver et al. (2007).

The CO_2 concentration profiles from the scenarios that use the 360 GtC budget are shown in Fig. 2. The peak in the atmospheric concentration of CO_2 is higher and earlier than under the 430 GtC scenarios, reflecting the reduction in the strength of carbon sinks due to the feedback effects. A sharper reduction in emissions and the concentration of CO_2 is necessary in the latter part of the century to return the concentration to a level consistent with a 450 ppm CO_2-e outcome in the early- to mid-2100s.

3.4. Step 2: Emissions estimates for the period 2001–2010

Global fossil CO_2 emission estimates for the period 2001–2006 were obtained from the Carbon Dioxide Information Analysis Centre (CDIAC) (Boden et al., 2009). Preliminary global fossil CO_2 emission estimates published by CDIAC were also used for 2007 and 2008 (Marland and Boden, 2009). In 2009, it was assumed that global fossil CO_2 emissions fall by 2.6%, slightly less than the 2.8% decline predicted by Le Quéré et al. (2009). The 2010 global fossil projection was calculated as the sum of the forecasts for developed and developing country emissions, resulting in projected growth of global emissions of 2.4% for the year.

Global LUCF emission estimates for the period 2001–2005 were obtained from Houghton (2008). For the period 2006–2008, the global LUCF emission estimates from Le Quéré et al. (2009) were used. In 2009 and 2010, global LUCF emissions were assumed to remain stable at 2008 levels.

Developed and developing country fossil and LUCF emission estimates for 2001–2006 were derived using data published by CDIAC (Boden et al., 2009; Marland and Boden, 2009; Houghton, 2008) and the UNFCCC Secretariat (UNFCCC, 2009a).[10] Bunker fuel emission estimates from UNFCCC (2009a) were assigned to the country where the fuel was uplifted in accordance with the existing UNFCCC accounting rules for memo items (IPCC, 2006).[11]

Developed country fossil CO_2 emission projections (excluding bunkers) for 2007 and 2008 were obtained from CDIAC (Marland and Boden, 2009). Developed country bunker fuel emission data for 2007 were obtained from UNFCCC (2009a). In 2008, developed country bunker fuel emissions were assumed to fall by 3% in response to the onset of the global financial crisis. In 2009, total developed country fossil CO_2 emissions were assumed to fall by 6.0% on account of the global financial crisis, before rising by 0.3%

[10] The UNFCCC emissions database (UNFCCC, 2009a) was mainly used as a secondary source to fill gaps in the data published by CDIAC.

[11] As with a number of areas, there is considerable uncertainty associated with bunker fuel emissions. See Ribeiro et al. (2007), Macintosh and Wallace (2009) and Buhaug et al. (2009).

in 2010. These assumptions were based on emerging data showing a sharp fall in emissions in certain developed countries in 2009[12] and the International Monetary Fund's October 2009 *World Economic Outlook*, which forecasts a decline in the real GDP of advanced economies of 3.4% in 2009 and a sluggish growth of 1.3% in 2010 (IMF, 2009).[13] Developed country LUCF emissions were assumed to remain at 2005 levels for the entire period 2006–2010.

Developing country fossil CO_2 emissions estimates for the period 2007–2009 were derived by subtracting the developed country estimate from the global estimate, providing emissions growth rates of 6.2%, 5.1% and 0.4% for 2007, 2008 and 2009 respectively. In 2010, developing country fossil emissions were assumed to grow by 4.2%, which is below both trend and a number of pre-financial crisis projections (Weyant et al., 2006; Clarke et al., 2007; Garnaut et al., 2008; Sheehan, 2008). Developing country LUCF emissions for the period 2007–2010 were calculated by subtracting developed country emissions from the global projection. This results in developing country LUCF emissions experiencing an 18% decline over the period 2005–2010, which is consistent with recent data showing a sharp fall in deforestation emissions in South America and southeast Asia since 2005 (National Institute for Space Research, 2009; Le Quéré et al., 2009; van der Werf et al., 2009).

3.5. Step 3: Emissions to 2020

Between 2011 and 2020, aggregate developed country CO_2 emissions (fossil plus LUCF) decline linearly to meet the relevant scenario's 2020 target for developed countries (i.e. 10–40% below 1990 levels). It was assumed for these purposes that surplus Assigned Amount Units (AAUs) from the first commitment period under the Kyoto Protocol are not carried forward. Estimates of the likely AAU surplus generally range between 10 $GtCO_2$-e and 13 $GtCO_2$-e, most of which emanate from Russia and Ukraine (Eliasch, 2008; AOSIS, 2009; den Elzen et al., 2009). If these AAUs are allowed to be carried forward, it will increase allowable emissions and possibly enable developed countries to remain on or near a BAU emissions trajectory (den Elzen et al., 2009; AOSIS, 2009).

Developing country fossil CO_2 emissions were assumed to grow by 1, 3 or 5%/yr between 2011 and 2020. Pre-financial crisis BAU projections of the likely rate of growth of developing country fossil CO_2 emissions over this period generally range between 2 and 5%/yr (Nakicenovic and Swart, 2000; Weyant et al., 2006; Garnaut et al., 2008; Sheehan, 2008; EIA, 2009b). How the global financial crisis will affect developing country emissions growth is currently unclear. Further, under the Copenhagen Accord, developing countries are expected to lodge and implement nationally appropriate mitigation actions, which should result in emissions deviating from BAU. However, considerable uncertainty remains about the precise nature of the mitigation commitments developing countries may adopt and the extent to which these commitments will be implemented. Judging how the interplay between relevant economic, legal and political factors will shape developing country fossil emissions over the period 2011–2020 is a difficult task. To account for this, the 1–5%/yr range was adopted.

From 2011, it was assumed that developing country LUCF emissions head on a linear path that would, if it continued beyond 2020, result in them reaching zero in 2030. This is similar to the proposal put forward in the Eliasch Review (Eliasch, 2008), which advocates for a halving of deforestation emissions by 2020 and for the global forest sector to be carbon neutral by 2030. It is also similar to the outputs from the SRES B1 scenarios, where developing country LUCF emissions reach zero between the late 2020s and the early 2030s (Nakicenovic et al., 2000).[14] Arguably, such an early and steep reduction in LUCF emissions is unrealistic due to the likelihood of ongoing deforestation pressures and the lack of capacity in relevant developing countries. On account of these factors, a number of other studies have projected much higher developing country LUCF emissions in the short- to medium-term, even in ambitious mitigation scenarios (Anderson and Bows, 2008). While acknowledging the difficulty of reducing developing country LUCF emissions, optimistic assumptions were adopted here to account for the potential for reductions in LUCF emissions under BAU or near-BAU conditions (Fisher et al., 2007) and to ensure conservative outputs concerning global emissions in 2020.

An additional factor in projecting developed and developing country emissions to 2020 is the offset credit market. Abatement that is covered by the recognised offset credit market does not result in a net reduction in global emissions; it merely redistributes them. If the impacts of offsets are not incorporated into announced commitments, there is the potential for double counting of abatement. To avoid this, an 'offset emissions component' was added to all scenarios. In devising this component, uncertainties in the offset market had to be taken into account. Under the Kyoto Protocol, developing countries can generate project-based offset credits via the Clean Development Mechanism (CDM) (Paulsson, 2009). In the post-2012 climate regime, new offset mechanisms may be introduced. There are proposals for the CDM to be transformed into a sectoral-based mechanism. The Copenhagen Accord also calls for the immediate establishment of a mechanism for reducing emissions from deforestation and forest degradation, and enhancing forest sinks, in developing countries (REDD-plus). Under the most likely market-based REDD scheme, offset credits would be generated if net forestry-related emissions (i.e. deforestation and forest degradation emissions less forest carbon stock enhancements) in developing countries were driven below a projected baseline.

To account for the likely expansion of the offset credit market, the offset emissions component was broken into two time periods. From 2011 to 2014, the international offset rules were assumed to remain the same as, or similar to, those applying during the Kyoto Protocol's first commitment period. During the first commitment period, registered CDM projects are expected to generate approximately 340 million Certified Emissions Reductions (CERs) per annum (UNFCCC, 2009c).[15] When projects in the pipeline are included, the average number of CERs over this period could rise as high as 580 million/yr (UNFCCC, 2009c). To calculate the offset emissions component during the period 2011–2014, the expected number of CERs was increased to 450 million/yr to account for the projects in the pipeline and the years outside of the first commitment period. This was then adjusted to remove the effect of CERs related to non-CO_2 greenhouse gases. To date, just over 50% of registered CDM projects concern abatement of non-CO_2 greenhouse gas emissions (IGES, 2009). On this basis, the offset emissions component was estimated to be 225 $MtCO_2$/yr to 2014 for all scenarios. By 2015, the international offset rules and institutions were assumed to have evolved, allowing for a broader range of offset mechanisms in the international climate regime. Depending on the stringency

[12] EIA (2009a), GGIOJ (2009) and Australian Department of Climate Change (2009b).

[13] See also OECD (2009).

[14] See also Rao et al. (2008).

[15] Each CER represents one tonne of CO_2-e.

Table 3
Offset emissions component in 2020, MtCO2.

Scenario family	COPENA10	COPENA15	COPENA20	COPENA30	COPENA40
Offset emissions component	228	409	613	1089	1657

of the developed country abatement targets, this could facilitate a significant increase in the international offset market. Accordingly, from 2015, the offset emissions component was assumed to increase linearly to reach a specified quantity in 2020, which differed depending on the scenario family (see Table 3). For the COPENA10 scenarios, the offset emissions component in 2020 was set at 20% of the CO_2-only abatement required in developed countries to meet the 10% target.[16] As Table 3 shows, this effectively results in no change in the international offset market. For each 5% increase in the developed country emission target for 2020, the offset emissions component as a proportion of required abatement was assumed to increase by 1.5%. For example, the offset emissions component under the COPENA15 scenarios was set at 21.5% of the required CO_2-only developed country abatement.[17] These assumptions were intended to capture the impacts of the increased demand associated with higher mitigation targets and the relationship between higher targets and calls for offsets in international negotiations.

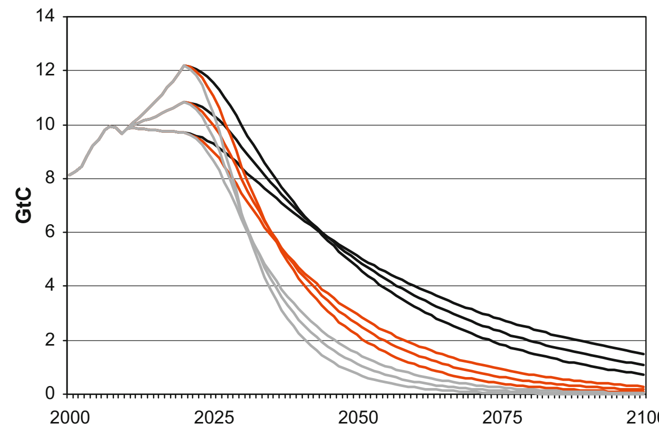

Fig. 3. COPENA10 scenarios, global CO2 emissions, 2000–2100. The scenarios with 560 GtC budgets are shown in black, scenarios with 430 GtC budgets in red, and scenarios with 360 GtC budgets in grey.

3.6. *Step 4: Post-2020 projections*

Total global CO_2 emissions peak in or before 2020, depending on the scenario. After 2020, there is likely to be transitional period during which the political and economic structures to facilitate the rapid decarbonisation of the global economy mature. To account for this, it was assumed that there is a 10-year period starting in 2021 in which the annual global CO_2 emissions abatement rate transitions smoothly to a maximum rate. Different assumptions regarding the transition period were adopted depending on the date at which global emissions peak.

- In scenarios where global emissions peak in 2020, it was assumed that the abatement rate declines linearly from an assumed rate of zero in 2020 to the maximum rate in 2030.
- In scenarios where emissions peak before 2020, it was assumed that the abatement rate declines linearly from the 2020 rate to the maximum rate in 2030.

In all scenarios, from 2031 to the close of the 21st century, global emissions decline exponentially at the maximum abatement rate obtained in 2030 while staying within the relevant cumulative emissions total for the scenario (i.e. 560, 430 or 360 GtC).

These assumptions are a modified version of those in Allen et al. (2009). They preclude the possibility of negative CO_2 emissions in the 21st century. Although negative emissions within this timeframe are not impossible, achieving such an outcome will be extremely difficult, requiring the development and widespread deployment of low cost zero or negative emissions energy technologies and near universal compliance with strict carbon containment rules. At the moment, this looks unlikely. Moreover, incorporating negative emission assumptions is arguably inconsistent with the precautionary principle contained in Article 3 of the UNFCCC.

4. Results

The results for the COPENA10, A20 and A40 family of scenarios are shown in Figs. 3–5. Table 4 contains the required global CO_2 emissions abatement rates for the period 2030–2100 from all of the COPEN scenarios. Table 5 provides the percentage change in global CO_2 emissions in 2050 off 2000 levels from these scenarios.

The results from this study are comparable to those from other low mitigation scenarios. This can be seen in Table 6, which contains details of the IPCC AR4 review of low mitigation scenarios and data from several post-AR4 scenario studies that are consistent with keeping warming within the 2 °C limit (i.e. <3.0 W/m2). The COPEN scenarios' required global CO_2 emission reductions in 2050 lie within the range from the cited literature. However, when the comparison is confined to the COPEN 360 GtC and 430 GtC scenarios (i.e. those that are more consistent with a ≤ 450 ppm CO_2-e outcome), it is apparent that they have relatively high 2050 emission reductions. This is attributable to four main factors. Firstly, unlike some other studies, the peaking date for global CO_2 emissions is delayed until 2020 in most of the relevant COPEN scenarios. Secondly, a number of COPEN scenarios have higher global CO_2 emissions over the period 2000–2020 than some other studies. This is mainly due to the fact that this study includes scenarios that have growth rates in developing country fossil CO_2 emissions of ≥ 3%/yr for the period 2010–2020. Thirdly, unlike many low mitigation scenarios–particularly those that aim to achieve radiative forcing levels of 2.6 W/m2 by 2100–the COPEN scenarios assume positive CO_2 emissions throughout the 21st century. Finally, the COPEN scenarios assume a constant

[16] Developed country CO_2 emissions were assumed to grow by 0.5% between 2011 and 2020 under BAU conditions, similar to EIA (2009b). This is lower than the rate projected in a number of other studies (Weyant et al., 2006; Clarke et al., 2007; Sheehan, 2008; Garnaut, 2008; Australian Department of Treasury, 2008). The lower growth rate was adopted on account of the global financial crisis and the extent to which it has affected a number of developed countries, particularly Russia and eastern European countries.

[17] This method is a modified version of that used in Australian Department of Treasury (2008). See also Eliasch (2008).

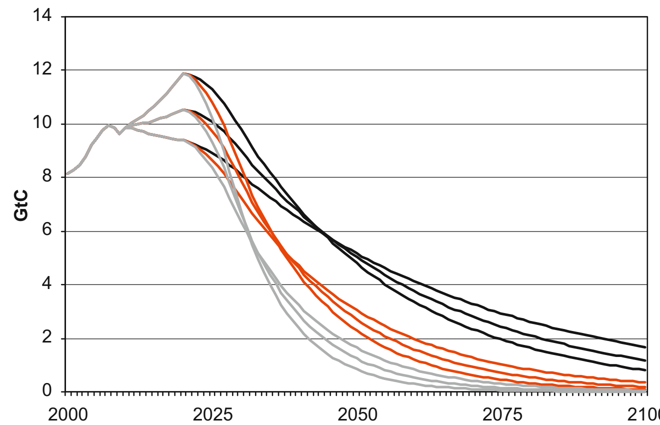

Fig. 4. COPENA20 scenarios, global CO2 emissions, 2000–2100. The scenarios with 560 GtC budgets are shown in black, scenarios with 430 GtC budgets in red, and scenarios with 360 GtC budgets in grey. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

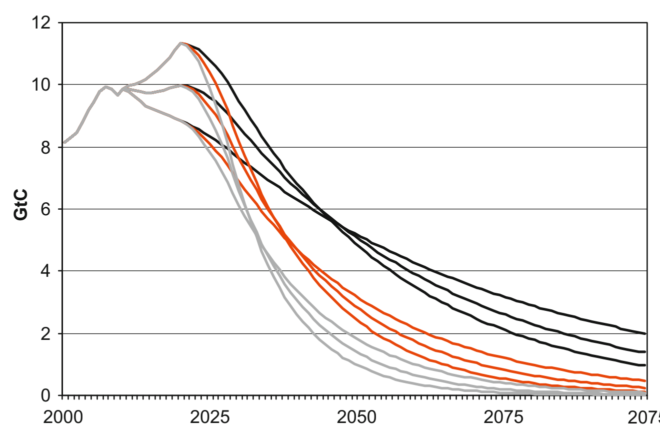

Fig. 5. COPENA40 scenarios, global CO2 emissions, 2000–2100. The scenarios with 560 GtC budgets are shown in black, scenarios with 430 GtC budgets in red, and scenarios with 360 GtC budgets in grey. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Table 4
Required global CO_2 emissions abatement rates, all scenarios, 2030–2100.

Scenario number	Annual rate of reduction 2030–2100 (%)				
	COPENA10	COPENA15	COPENA20	COPENA30	COPENA40
(1)560	−2.4	−2.3	−2.2	−2.1	−1.9
(3)560	−3.0	−2.9	−2.9	−2.7	−2.6
(5)560	−3.7	−3.6	−3.5	−3.4	−3.2
(1)430	−4.5	−4.4	−4.2	−4.0	−3.7
(3)430	−5.4	−5.3	−5.2	−5.0	−4.8
(5)430	−6.5	−6.4	−6.3	−6.0	−5.8
(1)360	−7.0	−6.8	−6.5	−6.1	−5.8
(3)360	−8.5	−8.3	−8.1	−7.7	−7.3
(5)360	−10.4	−10.1	−9.9	−9.5	−9.1

global CO_2 emissions abatement rate over the period 2030–2100, in contrast to a number of other scenario studies that seek to delay aggressive emission reductions until later in the 21st century in order to minimise abatement costs.

Table 5
Change in global CO_2 emissions in 2050, all scenarios (% of 2000 emissions).

Scenario number	Change in global CO_2 emissions in 2050 (% of 2000 emissions)				
	COPENA10	COPENA15	COPENA20	COPENA30	COPENA40
(1)560	−37	−37	−36	−36	−36
(3)560	−39	−38	−38	−38	−37
(5)560	−42	−41	−41	−40	−40
(1)430	−64	−63	−62	−61	−61
(3)430	−68	−67	−67	−66	−65
(5)430	−73	−72	−68	−71	−69
(1)360	−81	−81	−80	−78	−77
(3)360	−86	−85	−85	−83	−82
(5)360	−91	−90	−90	−89	−88

Table 6
Comparison of COPEN scenario results to other low mitigation scenarios.
Source: Fisher et al. (2007); van Vuuren et al. (2007); Garnaut (2008); Anderson and Bows (2008); Rao et al. (2008); van Vuuren et al. (2009); Calvin et al. (2009). See also Knopf et al. (2008).

Source	Atmos. CO_2-e concentration	Peak date for global CO_2 emissions	Change in global CO_2 emissions in 2050 (% of 2000 emissions)
IPCC AR4	445–490	2000–2015	−85 to −50
Post-AR4	≤ 450	2010–2020	−95 to −30
All COPEN	N/A	2010–2020	−91 to −36
COPEN 360 GtC/430 GtC	≤ 450	2010–2020	−91 to −61

5. Discussion

What is immediately apparent from the results (see Figs. 3 and 4 and Table 4) is the steepness of the curves for the scenarios that are consistent with the current direction of international negotiations. With a 560 GtC emissions budget for the period 2001–2100–i.e. the scenarios consistent with a 2 °C CWC–the required global CO_2 emissions abatement rate post-2030 (after the 10-year transition period) under the COPENA10-A20 scenarios is between 2.23 and 3.65%/yr. These abatement rates do not reflect what is likely to be necessary to keep warming within the 2 °C limit; only what would prevent > 2 °C warming from CO_2-only and excluding the possibility of significant positive forcing from non-CO_2 gases. The COPENA10-A20 scenarios based on the 430 and 360 GtC emissions budgets provide a more realistic approximation of what is likely to be required to stay within the 2 °C limit. Under the COPENA10-A20 scenarios based on the 430 GtC budget, the required abatement rates post-2030 range from 4.23%/yr to 6.53%/yr. For the COPENA10-A20 scenarios based on the 360 GtC budget, the required abatement rates range from 6.53%/yr to 10.40%/yr. The lower abatement rates from these 430 and 360 GtC scenarios are unlikely to reflect the actual required rate because they are based on the assumption that the growth in developing country fossil CO_2 emissions could be kept to 1%/yr over the period 2010–2020 if developed countries adopted a target of ≤ 20% below 1990 levels for 2020. The current position of major developing countries makes this unlikely.

Major developing countries have consistently called on developed countries to adopt aggressive abatement targets for the near-term, claiming that this is consistent with the principle of ‘common but differentiated responsibility’ that is enshrined in the UNFCCC. In July 2008 in Hokkaido, Japan, the Leaders of the

Group of Five (G5)–India, China, Brazil, South Africa and Mexico–issued a joint statement calling on developed countries to cut emissions by at least 25–40% below 1990 levels by 2020, and by between 80% and 95% below 1990 levels by 2050 (G5, 2008). A year later, in L'Aquila, Italy, the G5 issued another statement that urged developed countries to cut emissions by at least 40% below 1990 levels by 2020 (G5, 2009). The position of developing countries on this issue was largely maintained in the negotiations leading up to, and at, Copenhagen (IISD, 2009a, 2009b, 2009c). While the stance of the major developing countries may shift, it appears unlikely that they will adopt strong short- to medium-term commitments without a significant increase in developed country targets for 2020. Due to this, if developed countries adopt a combined target of between 10% and 20% below the 1990 levels for 2020, the minimum required global abatement rate post-2030 is likely to be $\geq 5\%$/yr.

Trying to objectively define a maximum rate of achievable global emissions reductions is an almost impossible task. What is obtainable at any point of time will depend on a combination of dynamic political, economic, technological and social factors. In his 2007 report, Stern (2007, p. 231) noted that 'experience suggests that it is difficult to secure emission cuts faster than about 1% per year except in instances of recession'. In an earlier study, Alcamo and Kreileman (1996, p. 318) tentatively suggested that a 'reasonable upper limit' of the global abatement rate is 2%/yr. Mignone et al. (2008, p. 260) effectively assumed a maximum achievable abatement rate of 3%/yr, stating that rates beyond this would be 'challenging at best'. Anderson and Bows (2008, p. 16) made similar observations, concluding that 'rarely are absolute annual carbon mitigation rates greater than 3 per cent considered viable'. Consistent with this observation, under the Garnaut 450 ppm CO_2-e scenario the average CO_2-e (i.e. Kyoto gases) and CO_2 abatement rates over the period 2012–2050 are 2.03%/yr and 2.36%/yr, respectively–although considerably higher abatement rates are assumed post-2050 (Garnaut, 2008).[18] The positioning of developed countries in the international negotiations appears to reflect an aversion to abatement rates in excess of $\sim 2\%$/yr, at least in the short- to medium-term. For example, if developed countries adopt a target for 2020 that is $\leq 20\%$ below the 1990 levels, their aggregate abatement rate over the period 2011–2020 in both CO_2 and the Kyoto gases (i.e. CO_2-e) will be $< 1.5\%$/yr.

While noting the subjectivity in any judgment about obtainable annual rates of abatement, rates significantly higher than 3–4%/yr appear to be unlikely—particularly prior to 2050—at least in the absence of a dramatic change in the global political environment and/or the rapid development and deployment of low cost zero or negative emissions technologies. This conclusion suggests that if developed countries adopt abatement targets of between 10% and 20% below the 1990 levels for 2020, as the current evidence suggests they will, there is a substantial risk the increase in the global average surface temperature will exceed 2 °C above the pre-industrial levels.

As discussed, the failure of developed countries to adopt aggressive targets for 2020 has two effects: (a) it directly slows the rate of abatement; and (b) it decreases the probability that developing countries will adopt and implement substantial abatement commitments in the short- to medium-term. The scenarios here shed light on the relative importance of these two factors. Under the scenarios with a 560 GtC emissions budget, the difference between developed countries pursuing an aggregate target of 10% versus 40% below 1990 levels for 2020 equates to a 0.4–0.5%/yr difference in the required global abatement rate post-2030. Under the scenarios with a 430 GtC budget, the equivalent difference is 0.7–0.8%/yr. For scenarios with a 360 GtC budget, the difference is 1.1–1.3%/yr.

Changes in the growth rate of developing country fossil CO_2 emissions growth over the period 2010–2020 also have a significant impact on the required post-2030 abatement rate. Under the scenarios with a 560 GtC budget, for each rise of 1% in the annual growth rate of developing country fossil CO_2 emissions over this period, the global abatement rate post-2030 increases by 0.3%/yr. For the scenarios with a 430 GtC budget, each rise of 1% in the annual growth rate of developing country fossil CO_2 emissions between 2010 and 2020 increases the required post-2030 abatement rate by 0.5–0.6%/yr. For the 360 GtC scenarios, the equivalent increase in the abatement rate is 0.8–1.0%/yr.

The impacts of developed and developing country abatement commitments can be seen in the peak date of global CO_2 emissions. In the COPENA10 scenarios, global emissions only peak before 2020 if the growth rate of developing country fossil CO_2 emissions can be kept at $\sim 1\%$/yr over the period 2010–2020. Under the COPENA20 scenarios, the growth rate of developing country fossil CO_2 emissions for this period must be less than $\sim 2\%$/yr to ensure a pre-2020 peak in global emissions. In the COPENA30 and COPENA40 scenarios, the peak can be achieved with a developing country fossil CO_2 emissions growth rate of less than $\sim 3\%$/yr.

These results demonstrate that both developed and developing country abatement commitments for 2020 matter. They are also interrelated. Aggressive developed country targets can significantly and directly reduce the required global abatement rate after 2020. And the more aggressive the developed country targets for 2020, the greater the chance developing countries will adopt and implement strong near-term commitments, which will be crucial if there is a desire to keep warming within the 2 °C limit. As stated, the reverse also applies—higher developing country commitments directly decrease the required abatement rate post-2020 and increase the prospect of developed countries adopting aggressive abatement targets.

Irrespective of the nature of the international agreement that emerges from the current negotiations, keeping warming within the 2 °C limit will be challenging and require an unprecedented level of global cooperation and effort. The scenarios presented here illustrate this clearly. Only the scenarios with a 560 GtC budget have post-2030 abatement rates significantly below 4.0%/yr. Even then, if developed country targets are between 10% and 20% for 2020, the required global abatement rate post-2030 just to avoid a 2 °C CWC in the 21st century is likely to be in excess of 2.5%/yr, and it could be $> 3.5\%$/yr if developing country emissions growth is not significantly constrained. Of the 30 scenarios with 430 GtC and 360 GtC budgets, only two have a post-2030 global abatement rate below 4.0%/yr–COPENA30-(1)430 and COPENA40-(1)430. In these two scenarios, the required abatement rates are 3.97%/yr and 3.74%/yr, respectively.

The required abatement under all of the scenarios that rely on a 360 GtC budget is probably unachievable. The lowest post-2030 abatement rate (after the transition period) from these scenarios is 5.78%/yr (i.e. from COPENA40-(1)360). The implication of these results is that if climate–carbon cycle feedbacks are at the higher end of the range predicted by the IPCC models—and there is evidence that this may be the case (Canadell et al., 2007)—there is little chance that global temperatures will be able to be kept within the 2 °C limit. These results also suggest that the option of adopting a precautionary approach to the 2 °C limit on all other uncertainty grounds is effectively no longer available.

[18] The average CO_2-e abatement rate over the period 2051–2100 in the scenario is 6.63%/yr. Over the period 2051–2090 (i.e. before CO_2 emissions reach negative territory), the CO_2 abatement rate is 6.4%/yr.

Staying within the required emission constraints would require the global community to pursue a radical decarbonisation strategy post-2020 that is well beyond that currently being contemplated.
Geo-engineering solutions, which are speculative at this stage, may also be necessary to enhance the drawdown of carbon from the atmosphere and/or reduce incoming solar radiation.

In the scenarios presented here, it has been assumed that developing country LUCF emissions decline significantly between 2010 and 2020 (i.e. from 4.4 $GtCO_2$ to 2.2 $GtCO_2$), irrespective of developed country commitments and targets for the short- to medium-term. In all likelihood, a comprehensive and effective agreement on reducing emissions from deforestation and forest degradation will only occur in tandem with a broader agreement that includes strong developed and developing country commitments for 2020. As a result, if the international negotiations continue on their current path, the required global rate of abatement post-2030 is likely to be significantly higher than these scenarios indicate.

6. Conclusion

The results of this study suggest that if developed countries adopt an aggregate abatement target for 2020 of between 10% and 20% below the 1990 levels, global CO_2 emissions would probably have to be reduced by $\geq 5\%$/yr or more post-2030 (after a decade transitional period) in order to stay within the 2°C limit. In the absence of the capacity to reduce emissions dramatically over a short period of time in the latter half of the century, global CO_2 emissions would probably have to be $\geq 65\%$ below the 1990 levels in 2050–well beyond the 50% target proposed by the Group of Eight in 2008 and 2009 (G8, 2008, 2009).[19] These types of emission reductions do not appear realistic at this stage and could only be achieved with major political and economic upheaval and/or the rapid development and deployment of low cost zero or negative emission energy technologies.

Without a significant shift in the positioning of the major emitting countries concerning 2020 targets and commitments, the likelihood of warming being kept within the 2°C limit appears to be diminutive. To provide a realistic chance of meeting this objective, aggregate developed country CO_2 emissions would probably have to be $>30\%$ below the 1990 levels by 2020. Growth in developing country fossil CO_2 emissions would then have to be kept to $\sim$1%/yr to 2020. Relevant developing countries would also have to commit to, and implement, a radical plan to effectively eliminate LUCF emissions over a 30- to 50-year period. Comprehensive measures would also have to be introduced in all major emitting countries to control and reduce non-CO_2 greenhouse gas emissions. If these elements are agreed to and implemented, the required annual global CO_2 abatement rate post-2030 is likely to be $\sim$3–4%/yr. Many would argue on political and economic grounds that such rates are unrealistic. This may be correct. However, a global abatement rate significantly beyond 4%/yr is certainly approaching the unobtainable, at least without serious economic and political disruption.

The international climate negotiations in 2010 are arguably the last real opportunity to put in place the mitigation strategies that are required to keeping warming to 2 °C. The major emitting countries in particular have a choice. They can stay on the current negotiation path and accept that the 2 °C limit will, in all likelihood, be exceeded. Alternatively, they can alter their mitigation commitments to provide at least an outside chance of keeping warming within 2 °C. It is unrealistic to believe that developed countries can pursue moderate short- to medium-term abatement targets while aiming to keep the increase in the global average surface temperature below 2 °C above pre-industrial levels. This needs to be acknowledged in policy development processes. Equally, developing countries need to adopt and implement ambitious abatement plans if the 2 °C objective that is articulated in the Copenhagen Accord is going to be achieved. At the moment, there is a degree of inconsistency in the positioning of the major emitting countries. Most of them have expressed a desire to keep warming within the 2 °C limit but

[19] This target was also raised at the Copenhagen Conference but it was omitted from the Copenhagen Accord.

Table A1
Post-Copenhagen mitigation scenarios.

Family	Scenario number	Cumulative CO_2 emissions 2001–2100 (GtC)	Developed country 2020 abatement target (% below 1990)	Developing country annual fossil CO_2 emissions growth rate (%) 2010–2020
COPENA10				
	(1)560	560	10	1
	(3)560	560	10	3
	(5)560	560	10	5
	(1)430	430	10	1
	(3)430	430	10	3
	(5)430	430	10	5
	(1)360	360	10	1
	(3)360	360	10	3
	(5)360	360	10	5
COPENA15				
	(1)560	560	15	1
	(3)560	560	15	3
	(5)560	560	15	5
	(1)430	430	15	1
	(3)430	430	15	3
	(5)430	430	15	5
	(1)360	360	15	1
	(3)360	360	15	3
	(5)360	360	15	5
COPENA20				
	(1)560	560	20	1
	(3)560	560	20	3
	(5)560	560	20	5
	(1)430	430	20	1
	(3)430	430	20	3
	(5)430	430	20	5
	(1)360	360	20	1
	(3)360	360	20	3
	(5)360	360	20	5
COPENA30				
	(1)560	560	30	1
	(3)560	560	30	3
	(5)560	560	30	5
	(1)430	430	30	1
	(3)430	430	30	3
	(5)430	430	30	5
	(1)360	360	30	1
	(3)360	360	30	3
	(5)360	360	30	5
COPENA40				
	(1)560	560	40	1
	(3)560	560	40	3
	(5)560	560	40	5
	(1)430	430	40	1
	(3)430	430	40	3
	(5)430	430	40	5
	(1)360	360	40	1
	(3)360	360	40	3
	(5)360	360	40	5

are unwilling to take on the necessary commitments to achieve this objective.

Appendix A

See Table A1.

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