Keeping warming within the 2°C limit after Copenhagen

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Abstract

At the United Nations Climate Change Conference in Copenhagen in December 2009, the international community will try to establish a new legal architecture for addressing anthropogenic climate change. Many countries have expressed support for the notion that the objects of the international climate regime should include the desire to keep the increase in the global average surface temperature to a maximum of 2°C above pre-industrial levels. Achieving this objective will require strong near-term abatement commitments from developed and developing countries. At this point in the negotiations, it appears the aggregate abatement target for developed countries for 2020 will be between 10-20% below 1990 levels – well outside the 25-40% range that was included in the Bali Action Plan. This article describes 75 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 ≤20% below 1990 levels, global CO_2 emissions would probably have to be reduced by ~5%/yr or more post-2030 (after a decade transitional period) in order to stay within the 2°C limit. Without a significant shift in the negotiations, the likelihood of warming being kept within the 2°C limit appears to be diminutive.

1. Introduction

The object of the United Nations Climate Change Conference in Copenhagen in December 2009 is to reach agreement on the new international legal architecture for addressing anthropogenic climate change post-2012. Following the Bali Conference in 2007, detailed negotiations have been undertaken in two Ad Hoc Working Groups: the Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol (AWG-KP) and the Ad Hoc Working Group on Long-term Cooperative Action under the Convention (AWG-LCA). As its name suggests, the AWG-KP is discussing the future commitments of industrialised countries under the Kyoto Protocol. The AWG-LCA is negotiating an agreement on the strategy for achieving the objective of the United Nations Framework Convention on Climate Change (UNFCCC), namely to stabilise the atmospheric concentration of greenhouse gases at a level that will 'prevent dangerous anthropogenic interference with the climate system' (Art.2). According to the plan agreed to in Bali (the Bali Action Plan), this strategy will be based on 'a shared vision for long-term cooperative action' that will include a 'long-term global goal for emission reductions'.[1]

Although the objective of the UNFCCC and nature of the shared vision remain unclear, there is widespread support (at least at a superficial level) for a mitigation strategy that ensures the increase in the global average surface temperature does not exceed 2°C above pre-industrial levels. Over 100 countries have now adopted the 2°C limit as a policy objective (Pachauri and Reisinger, 2007; Meinshausen et al., 2009). In 2008, the Group of Eight (G8) – United Kingdom, Canada, France, Germany, Italy, Japan, Russia and the United States (US) – called for a global goal of 'achieving at least 50% reduction of global emissions by 2050' (G8, 2008, para. 23). The declaration issued by the G8 did not specify a date from which the reductions should be calculated. However, the endorsement of this vague abatement target was an indication of the G8's desire to pursue a mitigation strategy that kept global warming below ~2°C. A year later, on 8 July 2009 in L'Aquila, Italy, the G8 reiterated its desire for the international community to cut emissions by 50% by 2050 and tied this goal to the 2°C limit. It also indicated it would support a goal of reducing developed country emissions by 80% by 2050 'compared to 1990 or more recent years' (G8, 2009, para. 65).

The ambiguity in the language of the G8's declarations reflects the distance that still exists between the positions of a number of major polluting countries. This was evident in the declaration issued by the Major Economies Forum on Energy and Climate (MEF) at L'Aquila the day after the G8's declaration. Despite being pressured by the members of the G8, the major developing country emitters refused to endorse the 2°C limit or the 50% global emission reduction target. The final declaration of the forum merely stated:

> We recognize the scientific view that the increase in global average temperature above pre-industrial levels ought not to exceed 2 degrees C. In this regard and in the context of the ultimate objective of the Convention and the Bali Action Plan, we will work between now and Copenhagen, with each other and under the Convention, to identify a global goal for substantially reducing global emissions by 2050 (MEF, 2009).

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

Five months out from Copenhagen, it looks increasingly unlikely that an agreement will be reached that includes strong near-term mitigation targets and commitments. Failure to place tight restrictions on global emissions growth over the period 2010-2020 has profound implications for the chances of staying within the 2°C limit. This paper provides an estimate of the likely aggregate developed country abatement target for 2020. Using this information, simplified CO_2 mitigation scenarios are developed to 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.

2. Developed country emission limitation commitments for 2020

Developed countries are defined here as Annex I countries under the UNFCCC, including Turkey and Belarus.[2] A number of other industrialised countries may adopt binding emission limitation targets under the Kyoto Protocol (or a replacement agreement) for the period 2012-2020 (or 2012-2017). 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.

Rogelj et al. (2009) found that commitments given by developed countries to early June 2009 amounted to an aggregate reduction target for 2020 of between 8–14% below 1990 levels. More recent information suggests the target range is more likely to be between 10-20%. Table 1 contains the estimated abatement targets for developed countries that were used to arrive at this range. This finding is consistent with earlier estimates by Howes (2009).

[2] Neither Turkey nor Belarus currently has binding emission limitation commitments under the Kyoto Protocol.

Table 1 Likely developed country targets for 2020, change on 1990 levels, as at August 2009

Country	Low	High
Australia	-4	-24
Belarus	-5	-10
Canada	24	24
European Union (EU25)	-20	-30
Iceland	-15	-15
Japan	-9	-9
Liechtenstein	-20	-30
Monaco	-20	-20
New Zealand	-10	-20
Norway	-30	-30
Russia	-10	-15
Croatia*	-10	-20
Switzerland*	-20	-30
Turkey*	-10	-20
Ukraine*	-20	-20
United States*	-2	-23
Developed country aggregate target for 2020	**-10**	**-20**

Source: UNFCCC Joint Submission (2009); UNFCCC (2009); Larsen and Heilmayr (2009).
* Not officially declared. See below for further explanation.

The estimates were calculated using material provided by the parties to the AWG-KP and AWG-LCA (UNFCCC Joint Submission, 2009). High and low range estimates are provided to account for countries that have given pledges in the form of a range rather than a single abatement target. The 'low' column represents the weakest abatement target announced by the relevant countries. The 'high' column is the most aggressive abatement target. There is considerable uncertainty surrounding all of the targets, with the potential for significant shifts in negotiation positions before, and at, Copenhagen. There are also five developed countries that, at the time of writing, had not officially announced what targets they may be willing to adopt under a post-2012 agreement: Croatia, Switzerland, Turkey, Ukraine and the US.

The aggregate abatement target for 2020 for developed countries is influenced strongly by the position adopted by Russia and the US. Together they account for approximately 50% of Annex I emissions (UNFCCC, 2009). Russia has announced that it is willing to adopt an abatement target for 2020 of between 10-15% below 1990 levels. At first glace, this looks like a substantial reduction. However, Russia's emissions fell sharply in the early 1990s as a result of the economic upheaval that was associated with the collapse of the former Soviet Union. Although its emissions increased in the late 1990s and 2000s, they were still 29% below 1990 levels in 2006 (UNFCCC, 2009). Due to this, Russia's proposed abatement target would allow its emissions to increase by between 20-27% by 2020 from 2006 levels.

At the time of writing, the US Congress was considering several climate proposals, the main one being the *American Clean Energy and Security Act of 2009* (ACES Act) (otherwise known as the 'Waxman-Markey Bill'). The ACES Act contains a range of mitigation and adaptation measures, including an emissions trading scheme (ETS) that will account for approximately 85% of US emissions in 2005. Under the proposed ETS, covered emissions would be capped at 83% of 2005 levels in 2020 (i.e. 17% below 2005). The ACES Act will also establish a cap-and-trade scheme for hydrofluorocarbons (HFCs) that is aimed at phasing down the consumption of these gases. In addition to the ETS and HFC cap-and-trade scheme, further mitigation measures are provided for under the Bill, including performance standards for industrial emissions, energy efficiency programs and a substantial international forestry abatement program.[3] Analysis by the World Resources Institute suggests the reduction in US emissions by 2020 from the ACES Act could range between 15-33% below 2005 levels, depending on the environmental effectiveness of the complementary programs and international offsets (Larsen and Heilmayr, 2009). This range was used here to represent possible US targets under any new international agreement that might emerge from Copenhagen.

At the time of writing, neither Switzerland nor Ukraine had officially announced the targets they would be willing to adopt for 2020. However, both had provided information to the UNFCCC concerning the targets they were considering (UNFCCC Joint Submission, 2009). Switzerland was consulting on a target range for 2020 of between 20-30% below 1990 levels. Ukraine was considering a target of 20% below 1990 levels. In the absence of better information, these targets were used here.

The remaining two countries that have not announced firm 2020 emission reduction commitments (Turkey and Croatia) accounted for less than 2% of Annex I emissions in 2006 (UNFCCC, 2009). Hence, the targets they eventually adopt will not have a substantial influence on the aggregate developed country commitment. For current purposes, an arbitrary assumption was made that the aggregate target of these countries for 2020 will roughly reflect the range put forward by other developed countries – i.e. 10-20% below 1990 levels.

It is worth noting that both Turkey and Croatia are candidate countries to join the European Union (EU). When they join the EU, they will not necessarily form part of the EU for the purposes of accounting for its aggregate target. Whether this occurs will depend on the date they join the EU and the date the Union ratifies any post-2012 international climate agreement that emerges from Copenhagen. Due to the uncertainties surrounding these issues, the aggregate Annex I range of 10-20% was used rather than the EU range of 20-30%.

Although the current likely range of the aggregate developed country abatement target for 2020 is above that devised by Rogelj et al. (2009), it is still 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 (Metz et al., 2007). This range was adopted at the Bali Climate Conference 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

[3] The performance standards and energy efficiency programs overlap the ETS. Where this occurs, they will not result in a reduction in overall emissions.

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 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*.

Failure of developed countries to agree to cut emissions by between 25-40% by 2020 will have two deliterious affects 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 material abatement commitments in the short- to medium-term. Developing countries are likely to be reluctant to adopt significant abatement commitments unless the aggregate developed country target for 2020 falls within the 25-40% range. Even then, additional inducements (e.g. financial and technology transfers) will be necessary if developing country emissions are to be significantly constrained over the next one to two decades.

In the remainder of the paper, simplified CO_2 emissions mitigation scenarios are developed to illustrate the relative importance of these two factors and show what would have to be done post-2020 to stay within the 2°C limit if the direction of the international negotiations does not shift significantly in the coming months.

3. CO_2 emissions mitigation scenarios – method

Seventy-five CO_2-only emissions mitigation scenarios were developed for the above purposes. The decision to exclude non-CO_2 emissions was based on the desire for simplicity 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). The simplest method of analysing the relationship between CO_2 and non-CO_2 gases in mitigation pathways is the 'CO_2-plus' approach, where CO_2 emissions scenarios are developed in isolation and then a non-CO_2 component is added to estimate the net anthropogenic climate impact. The non-CO_2 component can be held constant across all scenarios (i.e. there is a single set of non-CO_2 emissions, atmospheric concentrations or radiative forcing assumptions that are added to the CO_2 scenario). 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).

The advantage of the CO_2-plus approach is its simplicity and ease of comprehension. 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. The CO_2-plus method was adopted here due to its simplicity and transparency.

Appendix A lists the 75 scenarios and associated key assumptions. There are five scenario 'families'– COPENA10, A15, A20, A30 and A40 – which reflect the assumed actual percentage reduction in 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, CH_4, N_2O, HFCs, PFCs and SF_6).

In each scenario family, there are 15 scenarios. The 'scenario number' – (1)560, (2)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 (e.g. 1-5) 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 GtC, 430 GtC and 360 GtC.

Cumulative 21st century CO_2 emissions

Building on the work of the likes of Allen et al. (2009), Anderson and Bows (2008) and Broecker (2007), a cumulative emission approach (or budget approach) was adopted to develop the scenarios. As Allen et al. (2009) explain, the projected CO_2-related temperature response is relatively 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 GtC, 430 GtC and 360 GtC. The 560 GtC budget was drawn from Allen et al. (2009), where cumulative emissions of 1TtC was used for the period 1750-2500 for a 2°C CWC. 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 to 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 arguably unrealistic. 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 cumulative CO_2 emissions over the 21st century were informed by the Garnaut Climate Change Review's 450 ppm CO_2-e stabilisation scenario (Garnaut, 2008). 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 at 2100, 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. As with other similar 450 ppm CO_2-e stabilisation scenarios, the Garnaut scenario is believed to provide a 50/50 chance of exceeding the 2°C limit.

Using a simple climate model – MAGICC, version 5.3.v2 (Wigley, 2009) – an iterative approach was adopted where the cumulative CO_2 emissions were adjusted under the scenario assumptions outlined 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. 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. Notably, 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 abatement scenarios with cumulative CO_2 emissions over the period 2000-2049 of 1437 $GtCO_2$ (393 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 350-400 GtC.

The CO_2 concentration profiles from every second scenario that uses the 430 GtC budget is shown in Fig. 1 (i.e. COPENA10-(1)430, COPENA10-(3)430 etc). 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 34.5 $GtCO_2$, consistent with Boden and Marland (2009) 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).

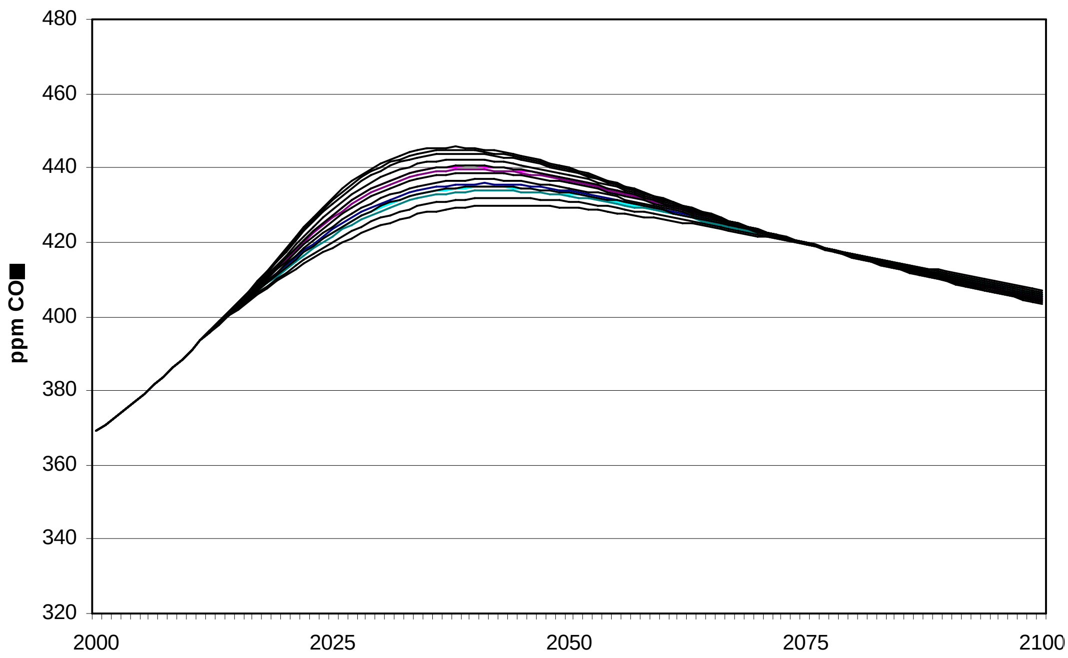

Fig. 1 Atmospheric concentration of CO_2 under scenarios with cumulative 21st century emissions of 430 GtC

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. $2xCO_2$ = 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.

The CO_2 concentration profile from every second scenario that uses the 360 GtC budget is 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 later 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.

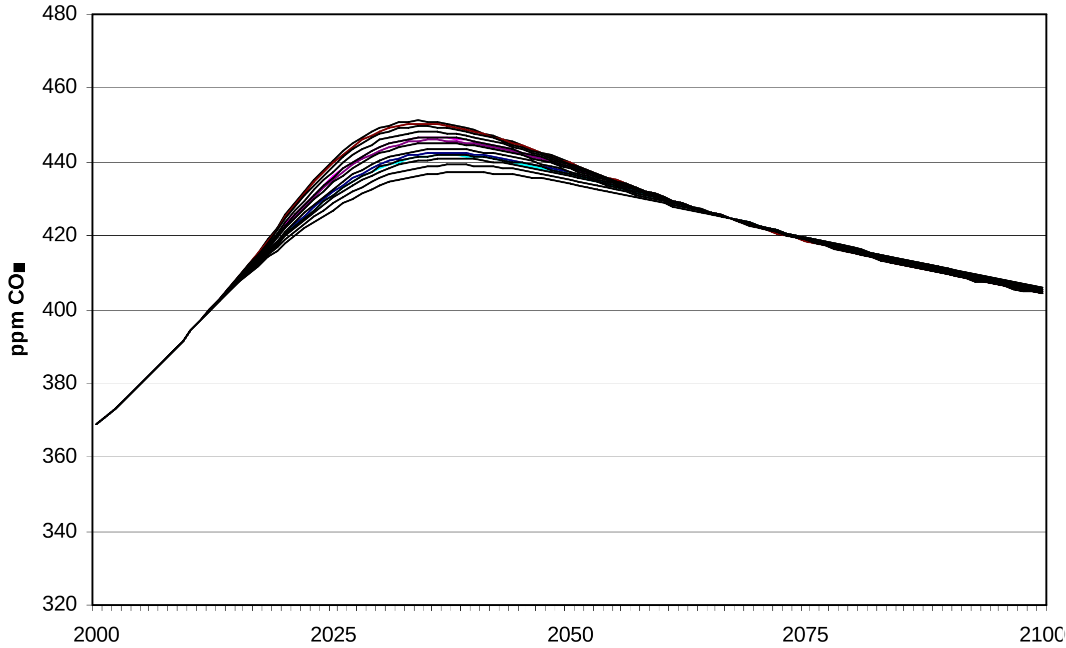

Fig. 2 Atmospheric concentration of CO_2 under scenarios with cumulative 21st century emissions of 360 GtC

Details of the data sources and assumptions used in developing the emission budgets and associated scenarios are provided below. The information is broken into four time periods for ease of comprehension: historic estimates; pre-2010 projections; 2010-2020 projections; and post-2020 projections.

Historic emission estimates

Global fossil CO_2 emission estimates for the period 1990-2006 were obtained from Boden and Marland (2009). Estimates for 2007 were obtained from Carbon Dioxide Information Analysis Centre (2008). Global LUCF emission estimates for the period 1990-2005 were obtained from Houghton (2008). Developed and developing country emission estimates were derived using Boden and Marland (2009), Houghton (2008) and UNFCCC (2009). Bunker fuel emissions were assigned to the country where the fuel was uplifted in accordance with the existing UNFCCC accounting rules for memo items (IPCC 2006).

Pre-2010 projections

In 2007, developed country fossil CO_2 emissions were assumed to grow by the average from the previous six years (0.6%). The grow rate was assumed to fall to 0.3% in 2008 to account for the onset of the global financial crisis. In 2009 and 2010, developed country fossil CO_2 emissions were assumed to stagnate at 2008 levels.

Consistent with the developed country projections for this period, developing country fossil CO_2 emissions were assumed to grow by the average from the previous six years (7.0%) in 2007. The grow rate is assumed to fall to 3.5% in 2008 and, in 2009 and 2010, it drops to 1% in both years.

Developed and developing country LUCF emissions were assumed to remain at 2005 levels for the period 2006-2009.

2010-2020 projections

Developed country LUCF emissions are assumed to stabilise at zero in 2010 and remain there through to 2020. Between 2011 and 2020, aggregate developed country fossil CO_2 emissions decline linearly to meet the relevant scenario's 2020 target for developed countries (i.e. 10-40% below 1990 levels).

Developing country fossil CO_2 emissions are assumed to grow by between 1-5%/yr between 2011 and 2020. There is significant uncertainty about the rate at which developing country fossil CO_2 emissions are likely to grow over this period. Business-as-usual (BAU) projections generally range between 2-5%/yr (Nakicenovic and Swart, 2000; Weyant et al., 2006; Garnaut et al., 2008; EIA, 2009). The difficulty of projecting developing country fossil emissions over this period has been increased by the global financial crisis. It will be several years before the full impacts of the crisis on economic growth, energy use and emission trends in developing countries will be clear. The scenarios here are mitigation scenarios, meaning the business-as-usual projections have to be modified to take into account the outcomes of the international climate negotiations and other domestic initiatives. Judging how the interplay between the relevant economic and political factors will shape developing country fossil emissions over this period 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 2040. This is similar to the assumptions adopted in the Garnaut Climate Change Review's 450 and 550 ppm CO_2-e scenarios (Garnaut, 2008).[4] Arguably, such an early and steep reduction in LUCF emissions is unrealistic due to the lack of capacity in relevant developing countries. While this may be correct, the Garnaut-like assumptions were adopted here for the period 2010-2020 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.

[4] In the Garnaut scenarios, LUCF emissions begin to fall in 2013 rather than 2011. The earlier start date was adopted here to ensure conservative outputs and to account for the potential for LUCF emission reductions since 2005.

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, A15, A20, A30 and A40 family of scenarios are shown in Figures 3-7. Tables 2-6 show the required global CO_2 emissions abatement rates for the period 2030-2100 from these scenarios, along with the percentage global emission reduction below 1990 levels for 2030, 2040 and 2050.

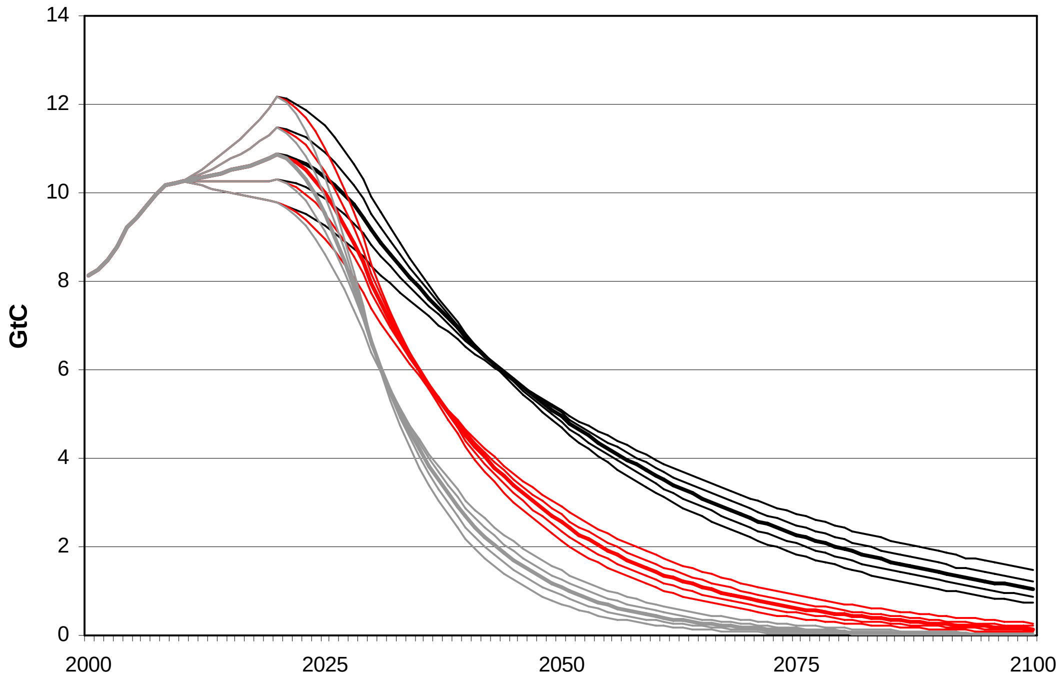

Fig. 3 COPENA10 scenarios, global CO_2 emissions, 2000-2100. The scenarios with 560 GtC budgets are shown in black, scenarios with 430 GtC budgets in red, and scenarios with 360 GtC budgets in grey.

Table 2 COPENA10 scenarios – global CO_2 emission reductions, annual abatement rate and % below 1990 levels in selected years

Scenario number	**Annual rate of reduction (%) 2030-2100**	**% change on 1990**			
		2020	**2030**	**2040**	**2050**
(1)560	-2.44	25	7	-16	-35
(2)560	-2.77	32	13	-15	-35
(3)560	-3.04	39	18	-14	-37
(4)560	-3.34	47	22	-13	-38
(5)560	-3.67	56	27	-12	-40
(1)430	-4.57	25	-5	-41	-63
(2)430	-5.08	32	-1	-41	-65
(3)430	-5.53	39	2	-42	-67
(4)430	-6.02	47	5	-44	-70
(5)430	-6.58	56	8	-45	-72
(1)360	-7.11	25	-18	-61	-81
(2)360	-7.93	32	-16	-63	-81
(3)360	-8.68	39	-15	-66	-86
(4)360	-9.55	47	-14	-69	-89
(5)360	-10.56	56	-15	-72	-91

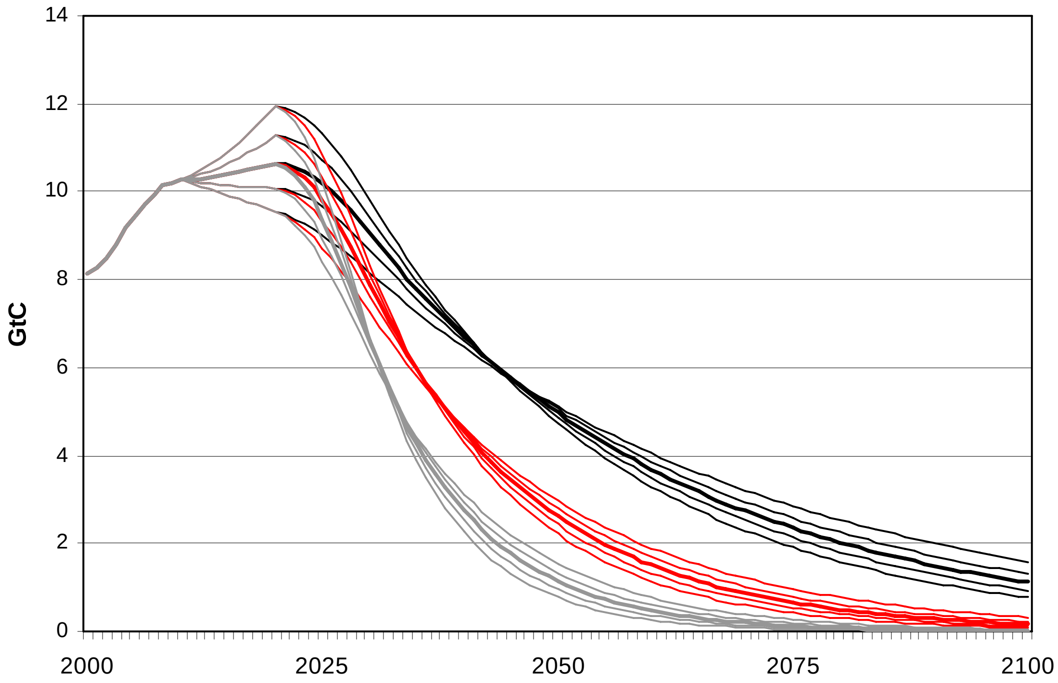

Fig. 4 COPENA15 scenarios, global CO_2 emissions, 2000-2100. The scenarios with 560 GtC budgets are shown in black, scenarios with 430 GtC budgets in red, and scenarios with 360 GtC budgets in grey.

Table 3 COPENA15 scenarios – global CO_2 emission reductions, annual abatement rate and % below 1990 levels in selected years

Scenario number	Annual rate of reduction (%) 2030-2100	% change on 1990			
		2020	2030	2040	2050
(1)560	-2.30	23	5	-17	-34
(2)560	-2.66	29	11	-15	-35
(3)560	-2.94	37	16	-14	-36
(4)560	-3.24	45	21	-13	-37
(5)560	-3.56	53	26	-12	-39
(1)430	-4.37	23	-7	-40	-62
(2)430	-4.90	29	-2	-41	-64
(3)430	-5.36	37	1	-42	-66
(4)430	-5.85	45	4	-43	-69
(5)430	-6.40	53	7	-45	-72
(1)360	-6.79	23	-19	-60	-80
(2)360	-7.63	29	-16	-62	-83
(3)360	-8.39	37	-15	-65	-85
(4)360	-9.24	45	-14	-68	-88
(5)360	-10.23	53	-14	-71	-90

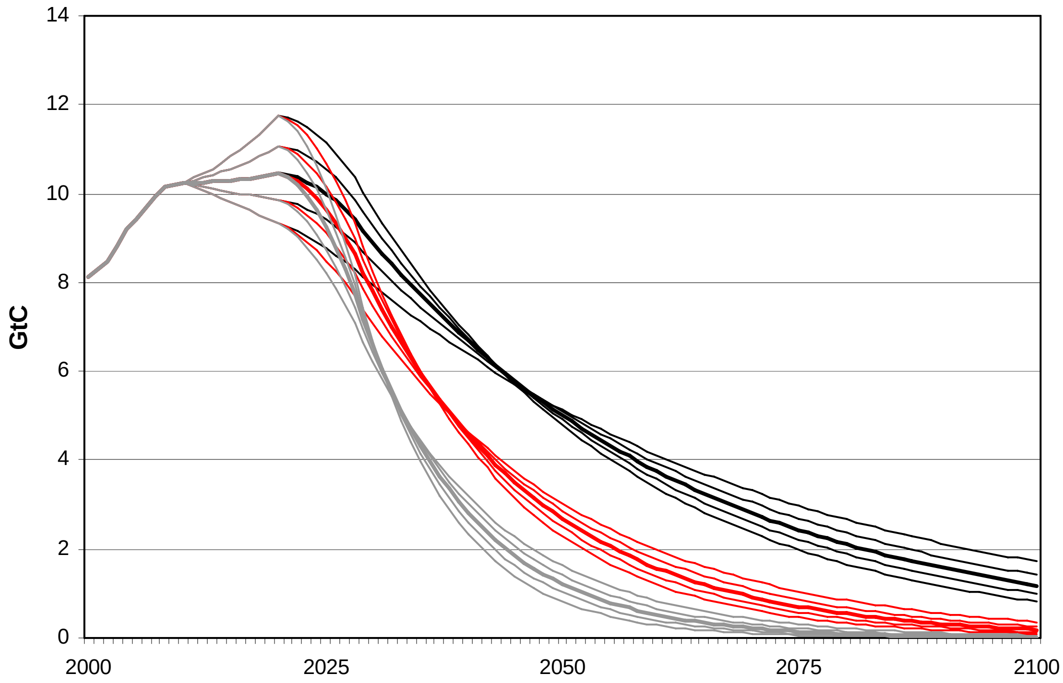

Fig. 5 COPENA20 scenarios, global CO_2 emissions, 2000-2100. The scenarios with 560 GtC budgets are shown in black, scenarios with 430 GtC budgets in red, and scenarios with 360 GtC budgets in grey.

Table 4 COPENA20 scenarios – global CO_2 emission reductions, annual abatement rate and % below 1990 levels in selected years

Scenario number	Annual rate of reduction (%) 2030-2100	% change on 1990			
		2020	2030	2040	2050
(1)560	-2.16	20	2	-18	-34
(2)560	-2.52	27	9	-16	-35
(3)560	-2.84	34	14	-14	-36
(4)560	-3.14	42	19	-13	-37
(5)560	-3.46	51	24	-13	-39
(1)430	-4.16	20	-9	-40	-61
(2)430	-4.69	27	-4	-41	-63
(3)430	-5.20	34	0	-41	-66
(4)430	-5.68	42	3	-42	-68
(5)430	-6.22	51	6	-44	-71
(1)360	-6.47	20	-20	-59	-79
(2)360	-7.29	27	-17	-61	-82
(3)360	-8.12	34	-15	-64	-84
(4)360	-8.94	42	-15	-67	-87
(5)360	-9.95	51	-14	-70	-89

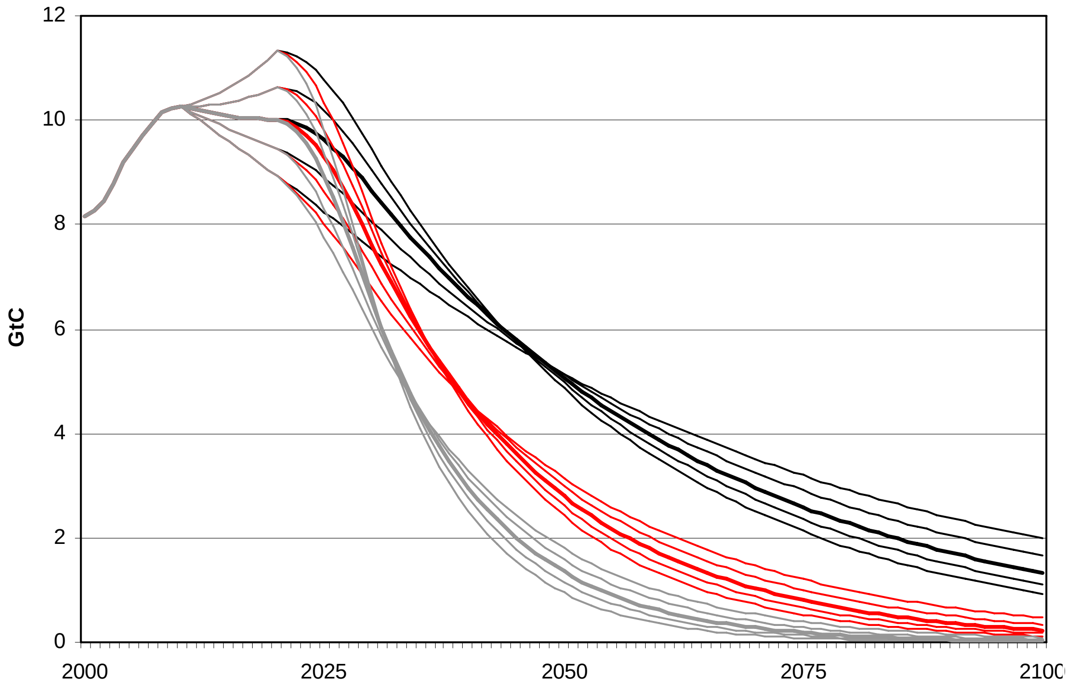

Fig. 6 COPENA30 scenarios, global CO_2 emissions, 2000-2100. The scenarios with 560 GtC budgets are shown in black, scenarios with 430 GtC budgets in red, and scenarios with 360 GtC budgets in grey.

Table 5 COPENA30 scenarios – global CO_2 emission reductions, annual abatement rate and % below 1990 levels in selected years

Scenario number	**Annual rate of reduction (%) 2030-2100**	**% change on 1990**			
		2020	**2030**	**2040**	**2050**
(1)560	-1.89	15	-3	-20	-34
(2)560	-2.24	21	4	-17	-34
(3)560	-2.64	29	11	-15	-35
(4)560	-2.94	37	16	-14	-36
(5)560	-3.26	45	21	-13	-37
(1)430	-3.76	15	-13	-41	-60
(2)430	-4.28	21	-8	-40	-61
(3)430	-4.87	29	-2	-41	-64
(4)430	-5.35	37	1	-42	-66
(5)430	-5.88	45	4	-43	-69
(1)360	-5.86	15	-23	-58	-77
(2)360	-6.65	21	-19	-59	-80
(3)360	-7.57	29	-16	-62	-83
(4)360	-8.37	37	-15	-65	-85
(5)360	-9.28	45	-14	-68	-88

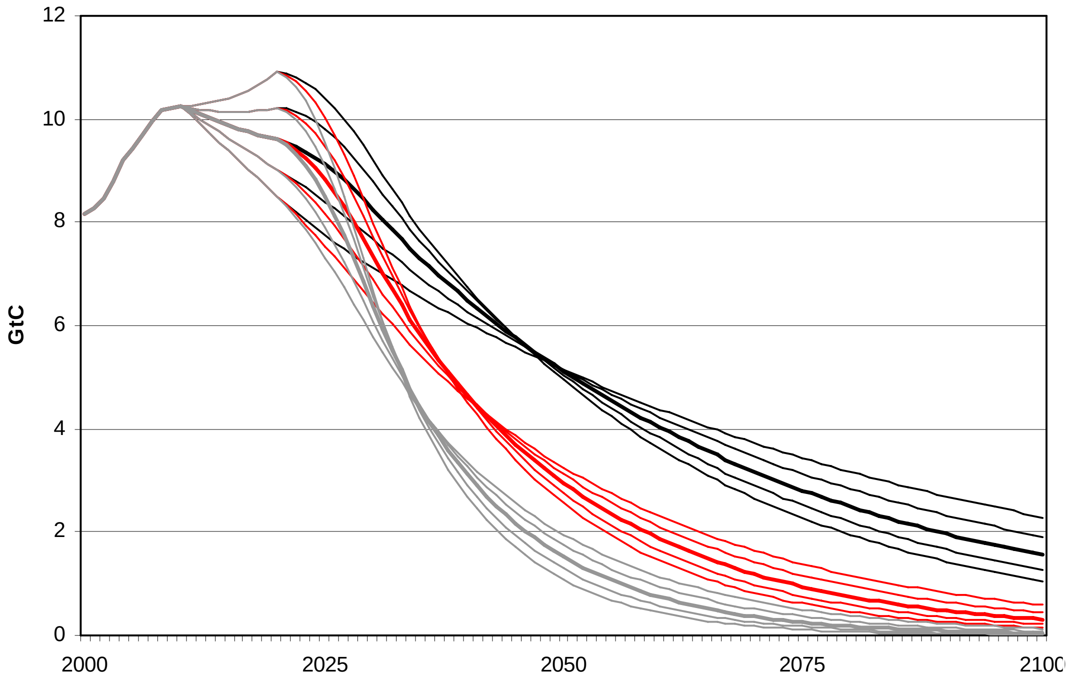

Fig. 7 COPENA40 scenarios, global CO_2 emissions, 2000-2100. The scenarios with 560 GtC budgets are shown in black, scenarios with 430 GtC budgets in red, and scenarios with 360 GtC budgets in grey.

Table 6 COPENA40 scenarios – global CO_2 emission reductions, annual abatement rate and % below 1990 levels in selected years

Scenario number	**Annual rate of reduction (%) 2030-2100**	**% change on 1990**			
		2020	**2030**	**2040**	**2050**
(1)560	-1.61	9	-9	-22	-34
(2)560	-1.97	16	-2	-19	-34
(3)560	-2.36	23	6	-17	-34
(4)560	-2.74	31	13	-15	-35
(5)560	-3.06	40	18	-13	-37
(1)430	-3.36	9	-17	-41	-58
(2)430	-3.87	16	-12	-40	-60
(3)430	-4.45	23	-6	-40	-62
(4)430	-5.02	31	-1	-41	-65
(5)430	-5.54	40	3	-42	-67
(1)360	-5.28	9	-26	-57	-75
(2)360	-6.03	16	-22	-58	-77
(3)360	-6.91	23	-18	-60	-80
(4)360	-7.82	31	-16	-63	-83
(5)360	-8.69	40	-15	-66	-86

5. Discussion

What is immediately apparent from Figures 3-7 is the steepness of the curves for all scenarios that are consistent with the current direction of international negotiations. With a 560 GtC emissions budget for the period 2001 to 2100 – i.e. the scenarios consistent with avoiding a 2°C CWC in the 21st century – the required global CO_2 emissions abatement rate post-2030 (after the 10-year transition period) under the COPENA10-A20 scenarios is between 2.16-3.67%/yr. For the COPENA10-A20 scenarios based on 430 GtC and 360 GtC emissions budgets, which arguably provide a more realistic approximation of the cumulative CO_2 emissions for the 21st century that are consistent with the 2°C limit, the minimum required abatement rate post-2030 is 4.16%/yr. This minimum is unlikely to reflect the actual required rate because it is 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 negotiating 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 80-95% 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). While the negotiating position 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 10-20% below 1990 levels for 2020, the minimum required global abatement rate post-2030 is likely to be ~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 Bowes (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).[5] The positioning of developed countries in the international negotiations appears to reflect an aversion to abatement rates in excess of ~2%/yr, at least in the short- to medium-term. For example, if developed countries adopt a target for 2020 of between 10-20% below 1990 levels, their aggregate abatement rate over the period 2011-2020 will be ~0.6-1.8%/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 10-20% below 1990 levels for 2020, as the current direction of negotiations suggests they will, there is a substantial risk the increase in the global average surface temperature will exceed 2°C above 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 take on substantial abatement commitments in the short- to medium-term. The scenarios here shed light on the relative importance of these two factors. For each additional 10% rise in the developed country target for 2020 under the scenarios with a 430 GtC budget, the required annual global abatement rate post-2030 falls by between 0.32-0.42%/yr. Consequently, the difference between developed countries pursuing an aggregate target of 10% versus 40% below 1990 levels for 2020 equates to 1.00-1.21%/yr difference in the global abatement rate post-2030. Under the scenarios with a 360 GtC budget, the equivalent difference is between 1.73-1.90%/yr and, for scenarios with a 560 GtC budget, the difference is between 0.60-0.83%/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 430 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 0.44-0.59%/yr. For the scenarios with a 360 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 0.75-1.01%/yr. For the 560 GtC scenarios, the equivalent increase in the abatement rate is between 0.27-0.40%/yr.

The direct and indirect effects of developed country targets 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 below 2%/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 ~2.5%/yr to ensure a pre-2020 peak in global emissions. In the COPENA30 and

[5] 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.

COPENA40 scenarios, the peak can be achieved with a developing country fossil CO_2 emissions growth rate of less than ~3-4%/yr.

These results demonstrate that both the direct and indirect effects of developed country targets 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.

Irrespective of the outcome at Copenhagen, keeping warming within the 2°C limit will be challenging and require an unprecedented level of global cooperation and effort over the coming decades. 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 10-20% for 2020, the required global abatement rate post-2030 just to avoid a 2°C CWC in the 21st century is likely to be ~3%/yr. Of the 50 scenarios with 430 GtC and 360 GtC budgets, only three have a post-2030 global abatement rate below 4.0%/yr – COPENA30-(1)430, COPENA40-(1)430, and COPENA40-(2)430; where the abatement rates range between 3.36-3.87%/yr. In the COPENA30-430 and COPENA40-430 scenarios, the post-2030 abatement rate only stays below or near 4.0%/yr if the developing country fossil CO_2 emission growth rate is kept below 3%/yr over the period 2010-2020.

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 5.28%/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. It would require climate sensitivity to be significantly below the current best guess of 3°C. Alternatively, post-2020 the global community would have to pursue a radical decarbonisation strategy that is well beyond that currently being contemplated. Geoengineering 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 5.4 $GtCO_2$ to 3.6 $GtCO_2$), 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 10-20% below 1990 levels, global CO_2 emissions would probably have to be reduced by ~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 ≥65% below 1990 levels in 2050 – well beyond the 50% target proposed by the G8. 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 negotiating position of developed and developing 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 prospect of meeting this objective, developed country targets for 2020 are likely to have to be ≥30% below 1990 levels. Growth in developing country fossil CO_2 emissions would then have to be kept below 2%/yr to 2020. Relevant developing countries would also have to commit to a radical plan to effectively eliminate LUCF emissions over a 30-50 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 ~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.

Copenhagen potentially presents the last real opportunity to put in place the mitigation strategies that are required to provide a realistic chance of keeping warming within the 2ºC limit. Developed countries in particular have a choice. They can stay on the current negotiation track, reach an agreement that sets low to moderate abatement targets and accept that the 2ºC limit will probably be exceeded. Alternatively, they can change their negotiating position to one that provides a chance of keeping warming within the 2ºC limit. It is unrealistic to believe developed countries can pursue moderate short- to medium-term abatement targets while aiming to keep the increase in the global average surface temperature below 2ºC above pre-industrial levels. This needs to be acknowledged in policy development processes. At the moment, there is an element of unreality about the positioning of developed countries. Many of them have expressed as desire to keep warming within the 2ºC limit but are unwilling to take on the necessary commitments to achieve this objective.

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Appendix: 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
	(2)560	560	10	2
	(3)560	560	10	3
	(4)560	560	10	4
	(5)560	560	10	5
	(1)430	430	10	1
	(2)430	430	10	2
	(3)430	430	10	3
	(4)430	430	10	4
	(5)430	430	10	5
	(1)360	360	10	1
	(2)360	360	10	2
	(3)360	360	10	3
	(4)360	360	10	4
	(5)360	360	10	5
COPENA15				
	(1)560	560	15	1
	(2)560	560	15	2
	(3)560	560	15	3
	(4)560	560	15	4
	(5)560	560	15	5
	(1)430	430	15	1
	(2)430	430	15	2
	(3)430	430	15	3
	(4)430	430	15	4
	(5)430	430	15	5
	(1)360	360	15	1
	(2)360	360	15	2
	(3)360	360	15	3
	(4)360	360	15	4
	(5)360	360	15	5
COPENA20				
	(1)560	560	20	1
	(2)560	560	20	2
	(3)560	560	20	3
	(4)560	560	20	4
	(5)560	560	20	5
	(1)430	430	20	1
	(2)430	430	20	2
	(3)430	430	20	3
	(4)430	430	20	4
	(5)430	430	20	5
	(1)360	360	20	1
	(2)360	360	20	2
	(3)360	360	20	3
	(4)360	360	20	4
	(5)360	360	20	5

COPENA30				
	(1)560	560	30	1
	(2)560	560	30	2
	(3)560	560	30	3
	(4)560	560	30	4
	(5)560	560	30	5
	(1)430	430	30	1
	(2)430	430	30	2
	(3)430	430	30	3
	(4)430	430	30	4
	(5)430	430	30	5
	(1)360	360	30	1
	(2)360	360	30	2
	(3)360	360	30	3
	(4)360	360	30	4
	(5)360	360	30	5
COPENA40				
	(1)560	560	40	1
	(2)560	560	40	2
	(3)560	560	40	3
	(4)560	560	40	4
	(5)560	560	40	5
	(1)430	430	40	1
	(2)430	430	40	2
	(3)430	430	40	3
	(4)430	430	40	4
	(5)430	430	40	5
	(1)360	360	40	1
	(2)360	360	40	2
	(3)360	360	40	3
	(4)360	360	40	4
	(5)360	360	40	5

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