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Climate-Carbon Cycle Feedbacks:
The implications for Australian climate policy

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Summary

The phrase ‘climate-carbon cycle feedbacks’ refers to the interaction between temperature change, atmospheric carbon dioxide (CO_2) levels and the carbon cycle (i.e. the biogeochemical cycle by which carbon is exchanged between land, ocean and the atmosphere). Research has shown that global warming could significantly reduce the uptake and storage of carbon by land and ocean sinks. This risk has profound implications for climate policy. If the uptake and storage of carbon by natural sinks declines, a greater proportion of each additional unit of carbon emissions will remain in the atmosphere (called the ‘airborne fraction’). As a result, meeting any desired climate targets based on the atmospheric concentration of CO_2 will be more difficult, requiring a greater reduction in emissions than would otherwise be necessary.

The importance of climate-carbon cycle feedbacks is well-known in scientific circles, but often overlooked in policy processes. When discussing and analysing desired abatement targets, participants in policy processes often rely on data that do not fully account for these feedbacks. Unless corrective measures are taken, the use of these data could result in abatement targets being set too low and atmospheric CO_2 concentration objectives being exceeded.

Using data from advanced climate models that account for the interactions between climate change and the carbon cycle (called ‘coupled climate-carbon cycle models’), 21st century CO_2 emission budgets for developed and developing countries were calculated on the basis of the objective of stabilising the atmospheric concentration of CO_2 at 450 and 550 parts per million (ppm). These equate to concentrations of approximately 550 and 650 ppm of carbon dioxide equivalent (CO_2-e) respectively. According to the ‘best guess’ of the Intergovernmental Panel of Climate Change (IPCC), stabilisation of the atmospheric concentration of greenhouse gases at 550 ppm CO_2-e would lead to warming of approximately 2.9°C above pre-industrial levels. Stabilisation at 650 ppm CO_2-e is expected to lead to warming of around 3.6°C.

After calculating the 21st century emission budgets, emission trajectories were plotted to determine the level of abatement that is necessary to stay within the budgets. A scenario was also developed to determine whether 60 per cent mitigation targets for developed countries for 2050 (which is the Rudd Government's policy for Australia) are consistent with the objective of preventing dangerous climate change.

The results suggest that without a rapid and dramatic shift in the political landscape there is little chance of stabilising the atmospheric concentration of CO_2 at 450 ppm. It follows that there is little chance of keeping the increase in the global average surface temperature below 2°C above pre-industrial levels (2°C has been identified as the threshold for dangerous climate change

by many governments, policy organisations and scientists). A concerted effort from the international community will be required to achieve even an atmospheric concentration target of 550 ppm CO_2 (~650 ppm CO_2-e).

In order to have a reasonable chance of keeping the increase in the global average surface temperature to 2 – 3°C above pre-industrial levels, developed countries may have to pursue sharp emission reductions over the coming two decades. Developed country mitigation targets of 60 per cent below 2000 levels by 2050 are likely to fall well short of what is required to meet these global temperature targets.

While deep cuts in developed country emissions are required to meet 2 – 3°C temperature targets, developing country emissions must also be quickly stabilised and reduced. If the emission trends since 2000 are allowed to continue for much longer, the growth in developing country emissions will close off the option of keeping the atmospheric concentration of CO_2 below 550 ppm.

The results derived from the coupled climate-carbon cycle models are subject to a significant degree of uncertainty. The actual emission budgets that correspond to 450 and 550 ppm CO_2 atmospheric concentrations could be significantly higher or lower than those projected by the models used in this exercise. This raises a question about which data to rely on when devising emission budgets and abatement targets. Assuming the available climate models are equally valid, the answer will depend on judgments regarding risk, future generations and the environment.

Given the risks associated with tipping elements and the legal obligations and principles outlined in the UNFCCC, it is arguable that policy makers should be at least mildly risk averse when making abatement decisions. If a risk averse decision framework is adopted, data from coupled climate-carbon cycle models should be used in policy processes. The available data from these models indicate there is reason for concern if there is a desire to prevent the global average surface temperature increasing by more than 2 – 3°C above pre-industrial levels.

1. Introduction

The phrase 'climate-carbon cycle feedbacks' refers to the interaction between temperature change, atmospheric carbon dioxide (CO_2) levels and the carbon cycle (i.e. the biogeochemical cycle by which carbon is exchanged between land, ocean and the atmosphere). Research has shown that global warming could significantly reduce the uptake and storage of carbon by land and ocean sinks.[1] This risk has profound implications for climate policy. If the uptake and storage of carbon by natural sinks declines, a greater proportion of each additional unit of carbon emissions will remain in the atmosphere (called the 'airborne fraction'). As a result, meeting any desired climate targets based on the atmospheric concentration of CO_2 will be more difficult, requiring a greater reduction in emissions than would otherwise be necessary.

The level of understanding about the likely magnitude of carbon cycle feedbacks is relatively low, although it is developing rapidly. Advanced climate models have now been created that account for the interactions between climate change and the carbon cycle (called 'coupled climate-carbon cycle models'). The results from these models suggest that carbon cycle feedbacks are likely to play a critical role in determining the atmospheric concentration of CO_2 over the coming centuries (Friedlingstein *et al.* 2006; Denman *et al.* 2007; Meehl *et al.* 2007).

The importance of climate-carbon cycle feedbacks is well-known in scientific circles, but often overlooked in policy processes. When discussing and analysing desired abatement targets, participants in policy processes often rely on data that do not fully account for these feedbacks. Unless corrective measures are taken, the use of these data could result in abatement targets being set too low and atmospheric CO_2 concentration objectives being exceeded.

The Australian Government has a target of reducing Australia's emissions to 60 per cent below 2000 levels by 2050. This objective is consistent with the mitigation targets adopted in, and proposed by, a number of other developed countries, including the European Union (EU) and United Kingdom (UK). A 60 per cent abatement target by 2050 was also advised by Sir Nicholas Stern and has been adopted in a number of jurisdictions at the sub-national level (e.g, California, South Australia, New South Wales and the Australian Capital Territory) (ABC 2007a).

The purpose of this paper is to evaluate the implications of the available data on climate-carbon cycle feedbacks for policy processes aimed at preventing dangerous climate change (DCC). To do this, 21st century emission budgets for developed and developing countries are calculated and indicative emission trajectories are plotted. The paper also seeks to analyse whether 60 per cent

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[1] See Joos *et al.* (2001), Matthews (2005; 2006), Jones *et al.* (2006), Friedlingstein *et al.* (2006), Denman *et al.* (2007) and Meehl *et al.* (2007).

mitigation targets for developed countries for 2050 are consistent with the objective of preventing DCC.

Section 2 discusses the meaning of, and thresholds for, DCC. Section 3 provides an overview of the state of research on climate-carbon cycle feedbacks. Section 4 calculates 21st century CO_2 emission budgets for developed and developing countries using data from three climate-carbon cycle models. Section 5 evaluates how 60 per cent mitigation targets for developed countries for 2050 would affect developing country budgets. Section 6 discusses the results from sections 4 and 5. Section 7 provides a conclusion.

2. What are the thresholds for DCC?

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) states that its objective is to stabilise greenhouse gas concentrations at a level that would prevent 'dangerous anthropogenic interference with the climate system'. There is no generally accepted definition of this phrase. The second sentence in Article 2 provides that:

> Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

It has been argued that this sentence provides a three limb test for DCC: ecosystems must be allowed to adapt naturally to climate change, food production must not be threatened and economic development must be able to proceed in a sustainable manner (WBGU 2003). However, there is considerable uncertainty about the meaning of these concepts. What does natural adaptation of an ecosystem mean in the context of anthropogenic climate change? Is climate change dangerous when it threatens the integrity of one ecosystem or does the threat have to be more widespread? If climate change threatens food production in one region, is climate change dangerous or does the reference to food production refer to global markets? What does sustainable economic development mean in this context? As a matter of legal theory, DCC and the accompanying concepts in the second sentence in Article 2 must have a meaning. However, in reality, the UNFCCC envisages that the precise meaning of Article 2 and the thresholds for DCC will be the subject of negotiations between the parties.

In searching for a definition of DCC, governments will be influenced by scientific and economic issues. The natural sciences can provide information on impacts. Economics can attempt to monetarise the costs of action and inaction. While these different disciplines can inform the process, as Schneider and Mastrandrea have identified, determining the thresholds for DCC is 'ultimately a normative decision, influenced by value judgments, sociopolitical processes, and factors such as development, equity, sustainability, uncertainty, and risk' (Schneider and Mastrandrea, p. 15728). Of particular importance in this context is the fact that the adverse impacts of climate change will not be uniformly distributed across regions. Climate change that poses dangerous risks to one region may bring benefits for others. Different communities will also have different attitudes to risk, different values concerning the environment, economic growth and social issues, and different frameworks and processes for decision making. Given these factors, defining the 'optimal' mitigation targets and emissions pathway in order to avoid DCC are not technical issues; they are political judgments that will be made within applicable legal frameworks.

Although there is scope for legitimate differences in opinion about the thresholds for DCC, the UNFCCC contains a number of principles that are relevant to this issue and the design and implementation of abatement measures. The needs and circumstances of developing countries, especially those that are particularly vulnerable to the adverse effects of climate change, are required to be given 'full consideration'.[2] Parties are also required to take a precautionary approach to mitigation and adaptation issues. More specifically, parties are obliged, in their actions to achieve the objective of the Convention and to implement its provisions, to 'take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects'.[3] Adverse effects of climate change are defined in Article 1(1) as changes in the physical environment or biota which have 'significant deleterious effects' on natural and managed ecosystems, socio-economic systems or human health and welfare. In addition, the Convention states that parties shall be guided by the precautionary principle, which is defined in this context as follows.

> Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost.[4]

The emphasis on a precautionary approach is significant as it suggests that decision makers should display a degree of risk aversion when devising abatement measures, particularly to threshold effects or 'tipping points' in major natural systems. Changes in complex natural systems can often be discontinuous around system thresholds. Consequently, small changes near thresholds can trigger systems to switch into quantitatively different states, leading to irreversible impacts and potentially large losses in social welfare (Perrings and Pearce 1994). Lenton *et al.* (2008) have proposed the term 'tipping element' to describe major natural systems that are vulnerable to flipping to another state due to climate change. In their words, tipping elements are:

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[2] Article 3(2).
[3] Article 3(3).
[4] Article 3(3).

> ... subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances—into a qualitatively different state by small perturbations (Lenton *et al.* 2008, p. 1786).

Policy-relevant tipping elements identified by Lenton *et al.* (2008) include the loss of Artic summer sea ice, the melting of the Greenland and West Antarctic Ice Sheets, collapse of the Atlantic Thermohaline Circulation (THC) and dieback of the Amazon rainforest and boreal forests. The obligations contained in the UNFCCC suggest that, at the very least, the thresholds for DCC should be devised on the basis of minimising the risk of triggering these types of major threshold effects.

Drawing on these principles and other relevant policy issues, a number of governments, political entities, scientists and non-government organisations have argued the threshold for DCC is an increase in the global average surface temperature of around 2°C above pre-industrial levels or an atmospheric CO_2 or greenhouse gas concentration that is likely to result in an equivalent level of warming. Examples of organisations and individuals who have endorsed these thresholds are provided in Table 1 (see page 5).

The atmospheric CO_2 and greenhouse gas concentration targets listed in column three in Table 1 do not guarantee that the corresponding temperature threshold will be met. For example, a number of the entities have identified 450 parts per million (ppm) of carbon dioxide equivalents (CO_2-e) as accompanying a target of keeping the increase in the global average surface temperature to 2°C above pre-industrial levels. However, data in the Fourth Assessment Report (4AR) of the Intergovernmental Panel on Climate Change (IPCC) suggest that if the atmospheric concentration of greenhouse gases are stabilised at 450 ppm CO_2-e, there is only approximately a 50/50 chance that surface warming will be able to be kept to 2°C at equilibrium (Meehl *et al.* 2007). The 'likely range' (i.e. >66 per cent chance) of warming provided by the IPCC for stabilisation at 450 ppm CO_2-e is 1.4 – 3.1°C above pre-industrials, with a best guess of 2.1°C. If the atmospheric concentration of CO_2-e is stabilised at 550 ppm CO_2-e (~450 ppm CO_2), it is unlikely (<33 per cent chance) the increase in the average surface temperature will be less than 2°C above pre-industrials, and the IPCC's likely range is 1.9 – 4.4°C, with a best guess of 2.9°C. At 650 ppm CO_2-e (~550 ppm CO_2), the likely range is 2.4 – 5.5°C, with a best guess of 3.6°C (Meehl *et al.* 2007).

Table 1 Literature supporting thresholds for DCC at 2°C above pre-industrial levels or equivalent atmospheric concentration level

Source	**Temperature threshold (°C)**[a]	**Atmospheric concentration threshold**[b]
Allan *et al.* (2007)	2	<450 ppm CO_2-e
Stern (2007)		450 – 550 ppm CO_2-e
Harvey (2007)[c]		<410 ppm CO_2
Hansen (2005; 2007) and Hansen *et al.* (2007a; 2007b)	1.7	<450 ppm CO_2
European Union[d]	2	~450 ppm CO_2-e
WBGU (2007)	2	<450 ppm CO_2-e
Scientific Expert Group on Climate Change (2007)	2	
International Climate Change Taskforce (2005)	2	400 ppm CO_2
French Government (2004)	2	<450 ppm CO_2
European Climate Forum (2004)	2 – 3	
Ott *et al.* (2004) and den Elzen *et al.* (2007)	2	<450 ppm CO_2-e
Government of The Netherlands (2004)	2	
Swedish Government (2003)		<550 ppm CO_2-e
Climate Action Network (2002)	2	<450 ppm CO_2
Azar and Rodhe (1997)	2	375 ppm CO_2

a. Increase in global average surface temperature above pre-industrial levels.
b. CO_2-e is carbon dioxide equivalents, a measure of the concentration of the six main direct greenhouse gases (CO_2, CH_4, N_2O, SF_6, PFCs and HFCs). The abbreviation 'ppm' refers to parts per million.
c. Based on climate sensitivity (i.e. global average surface warming from a doubling of CO_2 concentration) 95th percentile of 4.5°C. Also assumes an overshoot. Without the overshoot, the limit is reduced to around 370 ppm CO_2.The Intergovernmental Panel on Climate Change (IPCC) states that the climate sensitivity is likely (>66 per cent chance) to be between 2 – 4.5°C, and it is very unlikely (<10 per cent chance) to be less than 1.5°C (IPCC 2007a).
d. See EU Council of Ministers (1996); European Parliament (2005; 2007), European Commission (2005; 2007), European Council (2007).

The risks associated with major tipping elements have been extremely influential in the choice of 2°C and corresponding atmospheric concentration targets as thresholds for DCC. Warming of 2°C above pre-industrial levels is unlikely to be without risk or harm. Several important tipping points may be reached with increases in the global average surface temperature of significantly less than 2°C. For example, irreversible melting of the Greenland Ice Sheet may be triggered by warming of 1.7°C above pre-industrial levels (i.e. ~1°C above the global average surface temperature in 2005), leading to sea level rise of between 2 – 7 metres (Hansen *et al.* 2007a; 2007b; IPCC 2007a; Lenton *et al.* 2008). There could also be complete loss of the Artic summer sea-ice with very little additional warming. As Lenton *et al.* (2008, p. 1789) remark, '[an Artic] summer ice-loss threshold, if not already passed, may be very close'. However, temperature increases above 2°C could trigger a series of additional large-scale discontinuities, including a series of cascading positive feedbacks that result in unexpectedly large temperature increases that are irreversible on human timescales, melting of the West Antarctic Ice Sheet and collapse of the THC. The threshold for a number of these tipping elements is believed to be warming of approximately 3 – 3.5°C above pre-industrial levels, although these estimates are subject to a high degree of uncertainty. In addition to the major tipping element risks, increases in the global average surface temperature greater than 2°C are associated with a number of other significant costs, including widespread biodiversity losses and adverse impacts on human health, water security and agricultural production.

If a risk averse decision framework is adopted, consistent with the principles outlined in the UNFCCC, the scientific evidence on the possibility of large-scale discontinuities suggests that, if a temperature threshold is used to define DCC and devise mitigation targets, it should be an increase in the global average surface temperature of no more than 2 – 3°C above pre-industrial levels. An average temperature increase in excess of 3°C would give rise to risks of severe widespread deleterious impacts. The same could be said of a 2°C threshold, although there is greater scope for disagreement with the lower temperature target.

In Australia, the Prime Minister, Kevin Rudd, has suggested that the international community should stabilise atmospheric greenhouse gas concentrations between 450 and 490 ppm CO_2-e. In the Leaders Debate held prior to the 2007 federal election, he stated in the context of the Australian Labor Party's 60 per cent mitigation target for 2050:

> Why do we pick this number 60 per cent? Because it comes from the science. Unless we are able to stabilise greenhouse gas emissions at something in the order of 450 – 490 parts per million, then frankly we place the planet in grave danger of not being able to correct itself (ABC 2007b).

The Prime Minister's reference to a target range of 450 – 490 ppm CO_2-e appears to have been drawn from a widely-cited table in Working Group III's

(WGIII) contribution to the 4AR (IPCC 2007b).[5] A truncated version of the table is set out below.

Table 2 Working Group III mitigation summary

CO_2 conc. (ppm)	CO_2-e conc. (ppm)	Global mean temperature increase above pre-industrial (°C)[a]	Peaking year for CO_2 emissions	Change in global CO_2 emissions in 2050 (% of 2000 emissions)
350-400	445-490	2.0-2.4	2000-2015	-85 to -50
400-440	490-535	2.4-2.8	2000-2020	-60 to -30
440-485	535-590	2.8-3.2	2010-2030	-30 to +5
485-570	590-710	3.2-4.0	2020-2060	+10 to +60
570-660	710-855	4.0-4.9	2050-2080	+25 to +85

Source: IPCC (2007b).

a. These estimates are the likely increase in the global average surface temperature at equilibrium using the "best estimate" climate sensitivity (i.e. 3°C).

The warming range provided in Table 2 for each atmospheric CO_2 and CO_2-e concentration range is not the full spectrum of possible or even likely results. The temperature response estimates are based on a best estimate of climate sensitivity (i.e. warming associated with a doubling of the CO_2 concentration from 280 to 560 ppm) of 3°C above pre-industrials, whereas the IPCC's likely range is 2 – 4.5°C. On this basis, Table 2 suggests that an atmospheric concentration of 445 – 490 ppm CO_2-e is likely to lead to an increase in the global average surface temperature of 2.0 – 2.4°C above pre-industrial levels. The desire to keep the increase in the global average surface temperature near 2°C appears to have motivated the Australian Prime Minister's choice of 450 – 490 ppm CO_2-e as a desirable target for global climate policy.

Table 2 suggests stabilising the atmospheric concentration of greenhouse gases within this range is still possible, provided CO_2 emissions peak before 2015 and global CO_2 emissions are reduced by at least 50 per cent below 2000 levels by 2050.[6] However, the peaking and mitigation columns in Table 1 (shaded grey) are outdated. The contribution of WGIII to the 4AR in relation to peaking and mitigation scenarios was based primarily on the contribution of Working Group I (WGI) to the Third Assessment Report, published in 2001 (IPCC 2001). Due to time constraints, WGIII was unable to incorporate recent scientific data that is discussed in the contribution of WGI

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[5] See IPCC (2007b), Tables SPM.5, 3.10 and TS 2.

[6] In 2005, the atmospheric concentrations of CO_2 and CO_2-e were 379 ppm and 455 ppm respectively (IPCC 2007a; Rogner *et al.* 2007).

to the 4AR on climate-carbon cycle feedbacks. This is alluded to in a footnote below the WGIII mitigation summary table, which states:

> The understanding of the climate system response to radiative forcing as well as feedbacks is assessed in detail in the AR4 WGI Report. Feedbacks between the carbon cycle and climate change affect the required mitigation for a particular stabilization level of atmospheric carbon dioxide concentration. These feedbacks are expected to increase the fraction of anthropogenic emissions that remains in the atmosphere as the climate system warms. Therefore, the emission reductions to meet a particular stabilization level reported in the mitigation studies assessed here might be underestimated (IPCC 2007b, SPM, p. 15).

Data are available that provide a basis on which to evaluate the implications of climate-carbon cycle feedbacks for global and national mitigation targets and thresholds for DCC. It is important that the available information on these feedbacks is incorporated into policy processes.

3. Climate-carbon cycle feedbacks

The risk posed by climate-carbon cycle feedbacks has been known for a considerable period of time. However, due to the complexities of the task, interactive modelling of climate-carbon cycle responses has been slow to develop. In recent times, steps have been taken to address this issue.

Central to this effort has been the Coupled Climate-Carbon Cycle Model Intercomparison Project (C^4MIP).[7] Under the C^4MIP, eleven climate models that accounted for carbon cycle feedbacks (seven coupled ocean-atmosphere general circulation models and four models of intermediate complexity) performed two simulations in accordance with a common protocol for the period 1860 to 2100 based on historical emissions (1860 – 1999) and the emission projections from the SRES (IPCC Special Report on Emissions Scenarios) A2 emission scenario (2000 – 2100). The first simulation allowed for the climate-carbon cycle feedbacks (called the ‘coupled simulation’). The second simulation sought to approximate what would happen if the carbon cycle was not affected by climate change (Friedlingstein *et al.* 2006).

The simulations produced a wide range of results. However, there was unanimous agreement amongst the models that there is a positive relationship between climate change and the carbon cycle. That is, climate change reduces the strength of the ocean and land sinks, which increases the airborne fraction, resulting in additional warming. The difference between the CO_2 concentration at 2100 under the coupled and uncoupled simulations ranged between 20 and 200 ppm. For six models, the range was between 50 – 100 ppm. Table 3 shows the airborne fraction of the cumulative CO_2 emissions over the period 1860 – 2100 from the eleven models under both

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[7] For discussion of the C^4MIP, see Friedlingstein *et al.* (2006).

the coupled and uncoupled simulations. The airborne fraction is higher under the couple simulations because of the reduction in the uptake of CO_2 by natural sinks. The cause of carbon cycle response is associated with warming and drying of terrestrial ecosystems and the potential for warming to reduce the transfer of carbon from the surface to the deep ocean (Friedlingstein *et al.* 2006; Denman *et al.* 2007; Friedlingstein 2008).

Table 3 Eleven model C^4MIP cumulative airborne fraction estimates for 1860 to 2100

Model	Coupled	Uncoupled
HadCM3LC	0.71	0.49
IPSL-CM2C	0.47	0.40
IPSL-CM4-LOOP	0.50	0.48
CSM1	0.53	0.52
MPI	0.53	0.45
LLNL	0.42	0.38
FRCGC	0.62	0.49
UMD	0.66	0.56
UVic-2.7	0.60	0.48
CLIMBER	0.57	0.51
BERN-CC	0.48	0.42

Source: Friedlingstein *et al.* (2006).

The implication from the results of the C^4MIP and other research[8] is that in order to stabilise atmospheric CO_2 concentrations at any given level, emissions must be reduced by more than if there was no positive climate-carbon cycle feedback. The emissions budget consistent with atmospheric stabilisation targets is reduced.

Recent research on trends in emissions and atmospheric CO_2 by Canadell *et al.* (2007) has produced results that are consistent with the outcomes of the C^4MIP modelling project, only the magnitude of the carbon cycle response is larger than forecast. They found that atmospheric CO_2 concentrations grew at an average rate of 1.93 ppm per year between 2000 and 2006; the highest rate recorded since monitoring begun in 1959 and significantly above the growth rates in previous decades. Preliminary data released by the US National Oceanic and Atmospheric Administration in April 2008 suggest this trend has continued, with the atmospheric CO_2 concentration rising by 2.4

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[8] See, for example, Joos *et al.* (2001), Matthews (2005; 2006) and Jones *et al.* (2006).

ppm in 2007 to almost 385 ppm (NOAA 2008). Canadell *et al.* (2007) attribute the increase in the growth rate to a combination of rapid global economic growth, an increase in the emission intensity of the global economy and an increase in the airborne fraction. The rise in the airborne fraction is due to a decline in the strength of land and ocean sinks, which is estimated to account for 18 per cent (±15 per cent) of the increase in the atmospheric CO_2 growth rate between 1970 – 1999 and 2000 – 2006. With regard to the declining efficiency of the sinks, Canadell *et al.* (2007, p. 18868) state:

> These results suggest that the observed carbon-cycle feedbacks occur faster than expected by our current understanding of the processes driving the sinks.

The results in Canadell *et al.* (2007) are subject to a degree of uncertainty. The airborne fraction fluctuates significantly between years due to climatic conditions and volcanic activity. Additional research will be required before definitive conclusions can be drawn. Yet the available data suggest there is reason for concern about the responsiveness of the carbon cycle to climate change and that climate-carbon cycle feedbacks should be taken into account when setting abatement targets.

4. Implications of climate-carbon cycle feedbacks for 21st century emission targets

The significance of the emerging evidence on climate-carbon cycle feedbacks for policy makers can be demonstrated using data analysed in the WGI contribution to the 4AR. The report contains data drawn from three climate-carbon cycle models (Hadley SM (HSM), UVic EMIC (UVic) and BERN2.5CC (BERN)) on the emission trajectories that are consistent with the stabilisation of atmospheric CO_2 concentrations at 450, 550, 750 and 1000 ppm. The outcomes of coupled and uncoupled simulations are provided.[9] The data from these simulations were obtained from the responsible IPCC scientists.[10] Figures 1 and 2 show the differences between the emission budgets for the 21st century from the Hadley SM, UVic EMIC and BERN2.5CC models for 450 and 550 ppm CO_2 stabilisation targets under the coupled and uncoupled simulations. These budgets assume there are no ‘overshoots’ (i.e. concentration levels do not exceed the stabilisation target – see section 6 for discussion on overshoot scenarios).

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[9] See Figure 10.21 in Meehl *et al.* (2007).

[10] Gian-Kasper Plattner and Thomas Stocker (pers. comms. 29 March 2008).

Figure 1 Coupled vs uncoupled 21st century emission budgets for 450 ppm CO_2 (HSM, UVic and BERN)

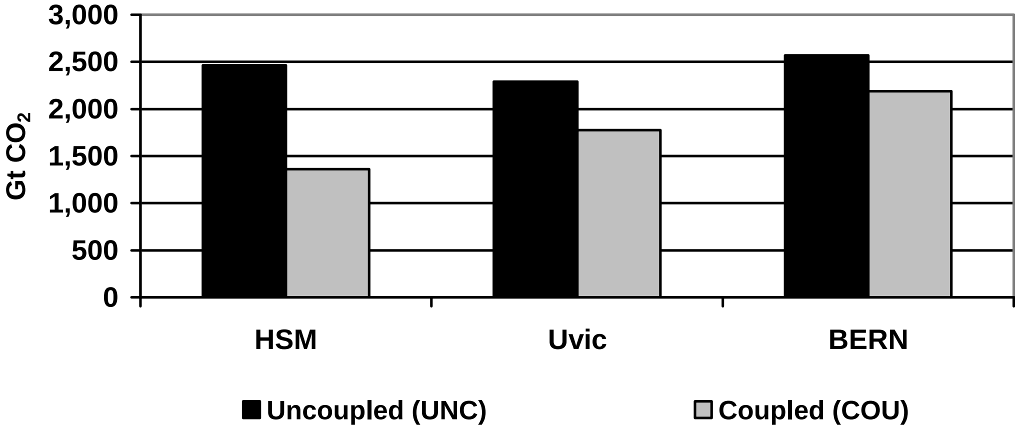
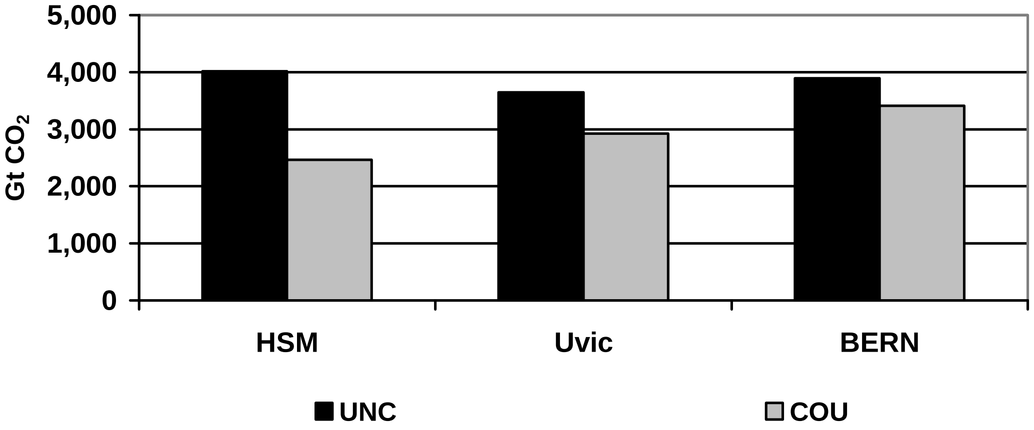


Figure 2 Coupled vs uncoupled 21st century emission budgets for 550 ppm CO_2 (HSM, UVic and BERN)



In all three models, the coupled budgets are significantly lower than the uncoupled budgets. For the 450 ppm budgets, the reductions range from 15 to 45 per cent. The 550 ppm budget reductions range from 12 to 39 per cent. The models are shown in ascending order of budget size for each stabilisation target under the coupled scenario (i.e. the HSM budgets are the smallest, the BERN budgets are the largest).

To evaluate the policy implications of the coupled 21st century emissions budgets, a hypothetical budget scenario was devised for developed and developing countries on the basis of the following assumptions.

- The global carbon budget for the 21st century was divided between Annex I (i.e. developed) and non-Annex I (i.e. developing) countries on the basis of population levels in 2000. Population data were obtained from the United Nations Statistics Division (UNSD 2008). This is one of many ways of dividing the global carbon budget between developed and developing nations. It was selected as a compromise between the interests of developed and developing countries and is intended to be indicative only. Actual national budgets, at least for the near-term, are currently being negotiated under the UNFCCC. After the national budgets have been determined, emissions trading should enable the exchange of allowances between countries. Theoretically, this should lead to a more efficient allocation of the global budget.

- Annex I carbon emissions for 2001 – 2005 were obtained from the UNFCCC Secretariat (UNFCCC 2008). From 2006 till the end of the first commitment period of the Kyoto Protocol in 2012, Annex I emissions were assumed to grow at the average growth rate from 2000 – 2005.

- Non-Annex I carbon emissions for 2001 – 2004 were derived by subtracting Annex I emission data from estimated global emissions. Data on global fossil emissions were obtained from the Carbon Dioxide Information Analysis Center (Marland *et al.* 2007) and global land use change emission data from Canadell *et al.* (2007). Annual global CO_2 emissions from land use change were assumed to be approximately 1.5 billion tonnes (Gt) of carbon (C) over the period 2001 – 2004 (Canadell *et al.* 2007). Between 2005 and 2012, non-Annex I emissions were assumed to grow at the average growth rate from 2000 – 2004. Between 2013 and 2020, non-Annex I emissions were assumed to continue to grow, but the growth rate was assumed to fall by 0.5 per cent each year over the period. Based on the current political positioning of the major developing countries, this can be considered a conservative assumption.

- It was assumed that global carbon emissions do not fall below the average for the period 2101 – 2300 suggested by the results of the relevant model. For example, the UVic model suggests the 450 ppm CO_2 stabilisation budget for 2101 – 2300 is approximately 884 Gt, implying an annual average of 4.4 Gt CO_2 over this period. On this basis, it was assumed emissions would not fall below 4.4 Gt CO_2 during the 21st century.

The scenario was run using the results from all three models. To aid comprehension, the following sections of the body of the paper only show the results derived using the 21st century global carbon budget from the UVic model. Selected results from the HSM and BERN runs are shown in Appendices A and B. The use of the UVic results does not indicate a preference for that model over the HSM or BERN models, or for the use of median budget numbers in policy processes. Indeed, there is an argument that lower budgets from reputable climate models should be preferred in order to minimise risk.

The results for the 450 ppm CO_2 stabilisation scenario are shown in Figures 3 (global trajectories) and 4 (Annex I and Non-Annex I trajectories). Figures 5 and 6 show the corresponding results for the 550 ppm CO_2 stabilisation scenario. The emissions trajectory is indicative only. It assumes a slow start up and that abatement becomes progressively more difficult as the baseline is approached. Table 4 provides indices of annual emission variations under the 450 and 550 ppm CO_2 coupled budgets for the period 1990 – 2050, assuming 2000 as the base year. The annual emission variation indices for the HSM and BERN under the 450 and 550 ppm CO_2 coupled budgets are provided in Appendix A for comparison.

Figure 3 UVic 450 ppm trajectory (uncoupled and coupled), global

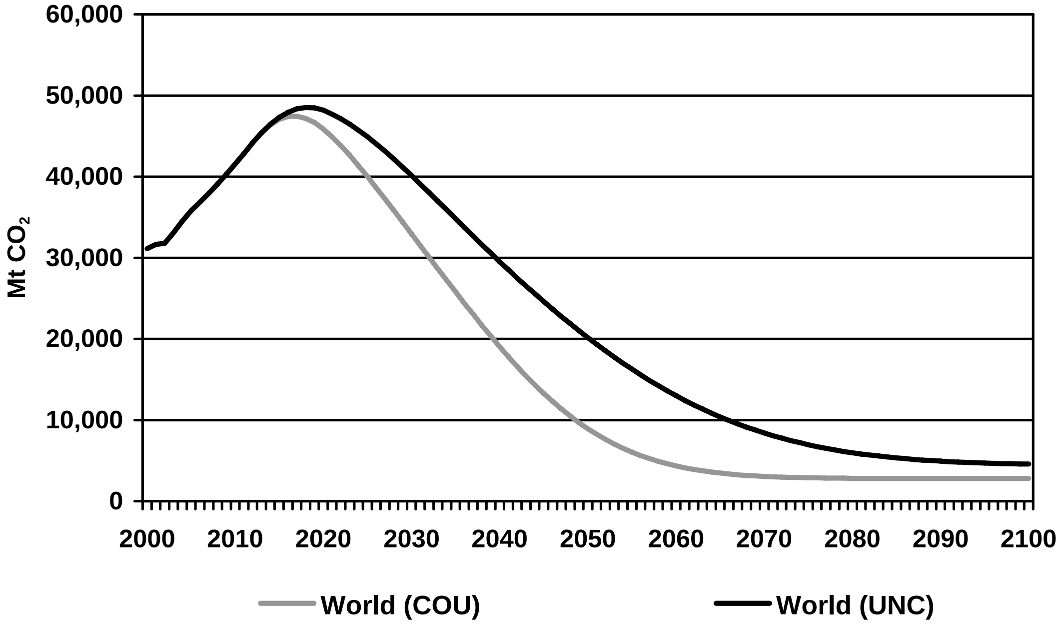


Figure 4 UVic 450 ppm trajectory (uncoupled and coupled), Annex 1 (A1) and non-Annex 1 countries (NA1)

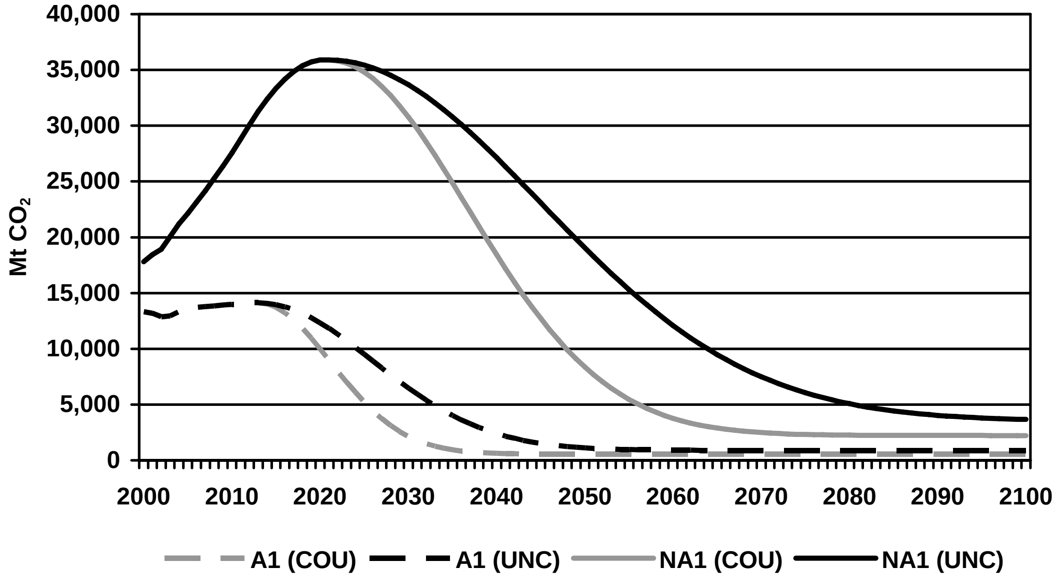


Figure 5 UVic 550 ppm trajectory (uncoupled and coupled), global

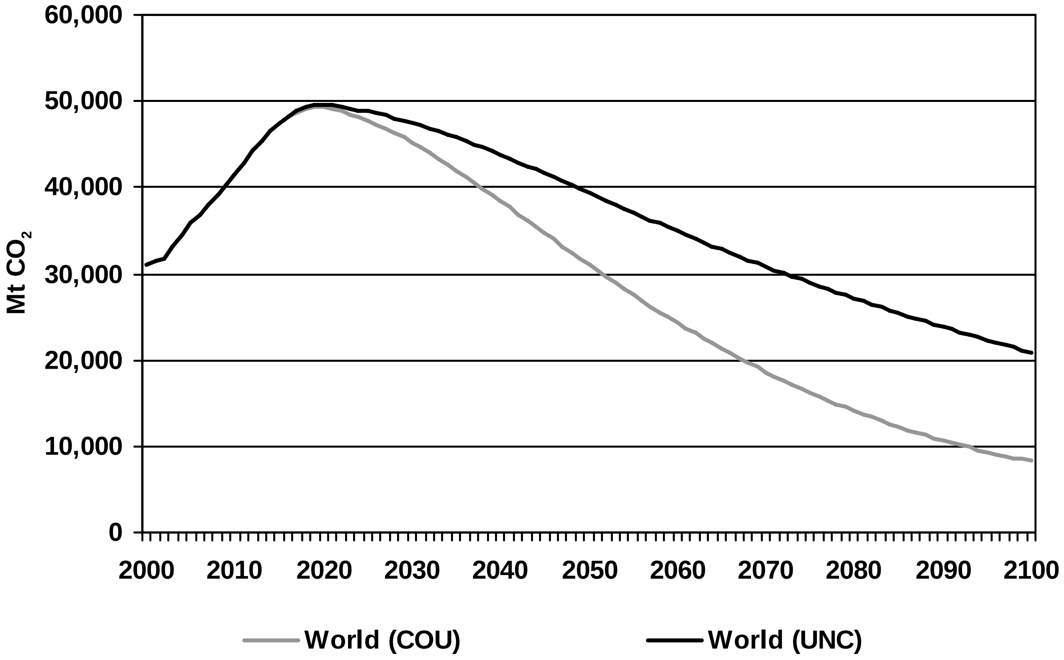


Figure 6 UVic 550 ppm trajectory (uncoupled and coupled), A1 and NA1

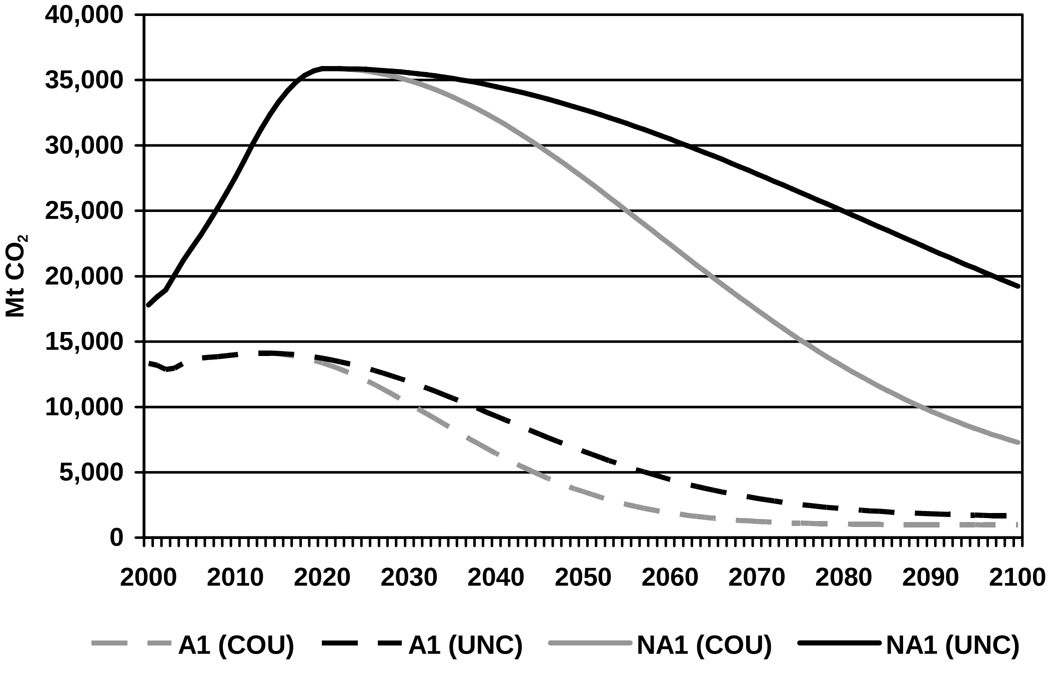


Table 4 Annual emission indices for UVic 450 and 550 ppm coupled budgets, 1990 – 2050, assuming 2000 as base year

	1990	2000	2020	2030	2040	2050
450 ppm						
Global	91	100	147	106	61	29
A1	103	100	75	16	5	4
NA1	82	100	202	173	104	47
550ppm						
Global	91	100	158	145	123	100
A1	103	100	100	77	48	26
NA1	82	100	202	197	180	155

5. Developed country 60 per cent by 2050 mitigation scenario

As discussed, a number of developed countries, including Australia, have proposed mitigation targets of reducing their emissions by 60 per cent on 1990 or 2000 levels by 2050. To gauge how a 60 per cent mitigation target for developed countries would affect developing country budgets under 450 and 550 ppm CO_2 scenarios, two mitigation scenarios were developed. The scenarios were the same as those outlined in Section 4, except that Annex I emissions decline in a linear manner from 2013 to reach 40 per cent of the 2000 levels in 2050. From 2050, Annex I emissions were assumed to continue to decline linearly before reaching 90 per cent below 2000 levels in 2100. The non-Annex I budget under both the 450 and 550 ppm CO_2 scenarios was calculated as the remainder from the global budget after the subtraction of Annex I emissions. The results for the UVic budgets are shown in Figures 7 and 8 for the 450 and 550 ppm CO_2 scenarios respectively. The emission trajectory is indicative only. Tables 5 and 6 provide indices of annual emission variations for the period 1990 – 2050, assuming 2000 as the base year. The annual emission variation indices for the HSM and BERN are provided in Appendix B for comparison.

Figure 7 UVic 450 ppm (coupled), A1 60 per cent mitigation scenario

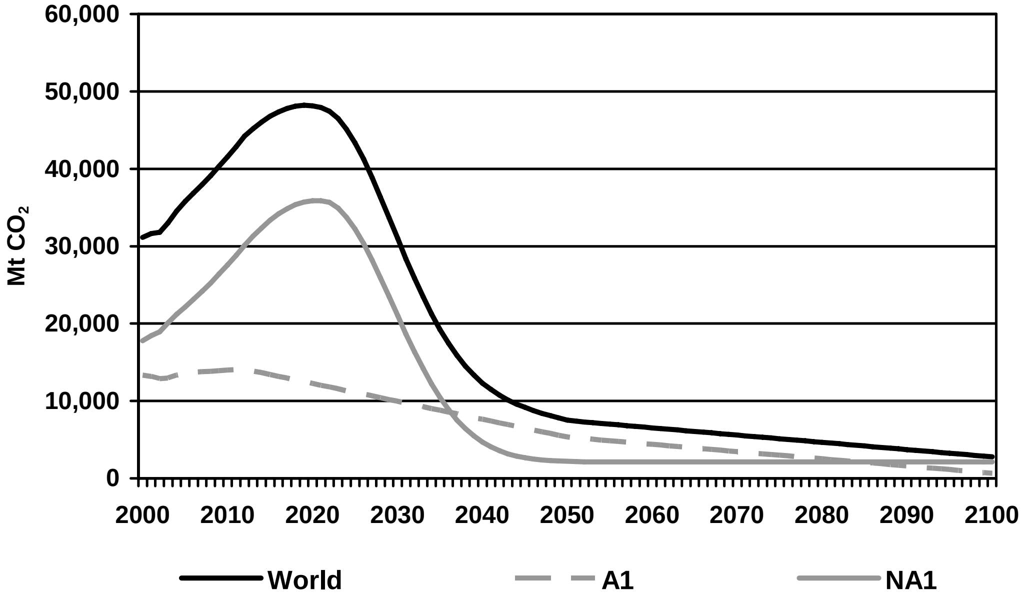


Table 5 Annual emission indices for 60 per cent mitigation scenario under UVic 450 ppm (coupled) budget, assuming 2000 as base year

	1990	2000	2020	2030	2040	2050
Global	91	100	155	100	40	24
A1	103	100	92	75	57	40
NA1	82	100	202	118	26	12

Figure 8 UVic 550 ppm (coupled), A1 60 per cent mitigation scenario

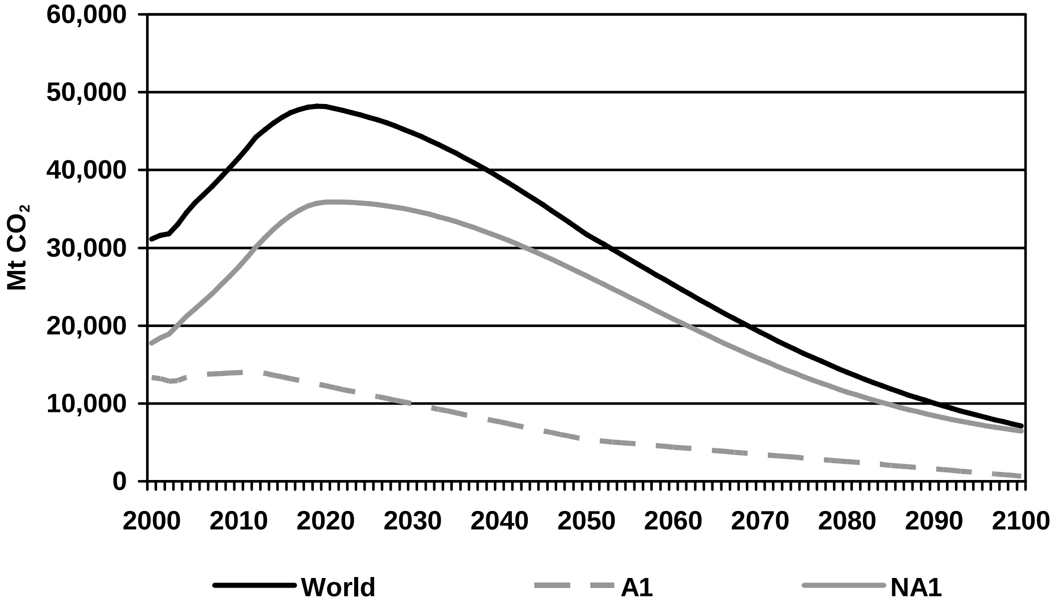


Table 8 Annual emission indices for 60 per cent mitigation scenario under UVic 550 ppm (coupled) budget, assuming 2000 as base year

	1990	2000	2020	2030	2040	2050
Global	91	100	155	144	125	102
A1	103	100	92	75	57	40
NA1	82	100	202	196	177	148

6. Discussion

The results from the above exercise suggest that it is highly unlikely that the atmospheric concentration of CO_2 will be able to be stabilised at or below 450 ppm (~550 ppm CO_2-e). The trajectory plotted using the UVic budget numbers shows global CO_2 emissions rising to almost 50 per cent above 2000 levels in 2020, then dropping sharply to 70 per cent below 2000 levels by 2050 (i.e. an 80 per cent drop in 30 years). To achieve this, Annex I emissions are 25 per cent below 2000 levels in 2020, roughly 85 per cent below in 2030 and 96 per cent below in 2050. Non-annex I emissions rise to just over 100 per cent above 2000 levels in 2020, then have to reach more than 50 per cent below 2000 levels by 2050 (i.e. a 77 per cent drop in 30 years). Without a rapid and dramatic shift in the political landscape, trajectories of this nature do not appear achievable.

In the absence of a major political shift, stabilisation around 550 ppm CO_2 (~650 ppm CO_2-e) appears to be a more likely outcome. Even this may be difficult. The trajectory derived from the UVic budget sees global emissions rising by 60 per cent between 2000 and 2020, before gradually returning to 2000 levels in 2050. Non-annex I emissions rise sharply initially, then fall to 55 per cent above 2000 levels in 2050. To accommodate the Non-annex I emissions within the global 550 ppm budget, Annex I emissions would still have to fall significantly over the first half of the 21st century. The trajectory shown In Figure 7 has Annex I emissions returning to 2000 levels by 2020, 25 per cent below 2000 levels by 2030 and roughly 75 per cent below by 2050. While the 550 ppm trajectories appear achievable in the current political, economic and technological environment, the stabilisation of the atmospheric concentration of CO_2 at this level would bring significant risks of severe climate impacts.

The implication that can be drawn from the HSM, UVic and BERN model data is that it may now be too late to achieve the objective of preventing the global average surface temperature from increasing by more than 2°C above pre-industrial levels. While probability assessments vary, if the atmospheric concentration of CO_2 exceeds 500 ppm (~600 ppm CO_2-e) it is likely the average surface temperature will increase by more than 2°C. At 500 ppm CO_2

(600 ppm CO_2-e) there is a good chance the increase in the global average surface temperature at equilibrium will exceed 4°C (Meehl *et al.* 2007).

As noted, there is a considerable degree of uncertainty about the strength of climate-carbon cycle feedbacks. The actual emission budgets that correspond to 450 and 550 ppm CO_2 atmospheric concentrations could be significantly higher or lower than those projected by the HSM, UVic and BERN models. This raises a question about which data to rely on when devising emission budgets and abatement targets. Should policy makers rely on first generation coupled climate-carbon cycle models? If so, which model or models should be used?

Assuming the available climate models are equally valid, the answer will depend on judgments regarding risk, future generations and the environment. As discussed, given the risks associated with tipping elements and the legal obligations and principles outlined in the UNFCCC, it is arguable that policy makers should be at least mildly risk averse when making abatement decisions. If a risk averse decision framework is adopted, data from coupled climate-carbon cycle models should be used in policy processes. The available data from these models indicate there is reason for concern if there is a desire to prevent the global average surface temperature increasing by more than 2 – 3°C above pre-industrial levels.

As the trajectories plotted in Section 4 show, the period to 2020 is of critical importance. If global emissions are not curbed in the next decade, there is a significant chance the atmospheric concentration of CO_2 will not be able to be stabilised below 550 ppm CO_2. To date, the focus of much of the debate about mitigation targets has been on 2050. If there is a desire to keep temperature increases near 2 – 3°C above pre-industrial levels, greater emphasis will have to be placed on near-term objectives. The key mitigation dates are 2020 and 2030, not 2040 and 2050.

The trajectories plotted in section 5 suggest that 60 per cent mitigation targets for developed countries for 2050 are incompatible with atmospheric CO_2 concentration targets of 450 ppm. The HSM, UVic and BERN model data indicate that keeping the atmospheric concentration of CO_2 to 450 ppm will be difficult, irrespective of what mitigation targets are pursued by developed countries. However, the adoption of a 60 per cent mitigation target for Annex I countries would render a 450 ppm CO_2 concentration target impossible.

The effect of a 60 per cent mitigation target for Annex I countries is more pronounced at lower atmospheric CO_2 concentration targets. As the concentration target increases, the global emission budget increases, thereby reducing the redistributive effects of the Annex I mitigation target on the Non-annex I budget. If a 500 ppm CO_2 target was adopted, the 60 per cent mitigation target would still substantially reduce the non-Annex I emission budget compared to the situation where the global budget was divided on the basis of population levels at year 2000. However, with a 550 ppm CO_2 budget, the effect of a 60 per cent Annex I mitigation target would be limited. The Non-annex I country targets would have to be reduced, but the reductions would not be dramatic. For example, the trajectory plotted using the UVic budget shows Non-annex I emissions would have to be 48 per cent above 2000 levels by 2050. In comparison, where the budget was split on the basis of population levels in 2000, Non-annex I emissions at the same date were 55 per cent above 2000 levels.

The plotted trajectories are normal stabilisation scenarios, meaning they do not account for the possibility of overshoots. Overshoot scenarios involve following a path whereby the atmospheric concentration of greenhouse gases and/or the global average surface temperature is allowed to exceed a specified target for a short period before being reduced to the desired stabilisation level. Such a trajectory would provide greater leeway for emissions over the short- to medium-term. This approach could be deliberately pursued, or it may come about as a result of a realisation that climate impacts are more severe and less desirable than previously believed.

There are several problems with overshoot strategies. Firstly, research by Matthews and Caldeira (2008) suggests that increases in the global average surface temperature are irreversible on human timescales. Once temperatures exceed the desired target, it is unlikely they will be able to be drawn down for hundreds of years.

Secondly, there is a risk that if the atmospheric concentration of greenhouse gases exceed certain thresholds, even for a relatively short period of time, dangerous impacts may be triggered that are irreversible (Stern 2007).

Thirdly, there is considerable uncertainty about the reductions in emissions that are necessary to stabilise and decrease the atmospheric concentration of CO_2. At present, approximately 36.7 Gt CO_2 (10 Gt C) is emitted annually from anthropogenic sources (Canadell *et al.* 2007; Friedlingstein 2008). Approximately 20.2 Gt (5.5 Gt C) of this is absorbed by terrestrial and oceanic sinks. On this basis, one could be lulled into thinking that the atmospheric concentration of CO_2 could be stabilised by reducing emissions to the level of the current natural sink (i.e. 20.2 Gt CO_2). If emissions were reduced to this level, emissions would initially stabilise. However, the uptake of CO_2 by the oceans would decline, and eventually cease, as the oceanic concentration of CO_2 equalises with the levels in the atmosphere (Friedlingstein 2008). To ensure the long-term stabilisation of the atmospheric concentration of CO_2, emissions would have to be reduced below the initial level of the natural sinks. In addition, climate-carbon cycle feedbacks are likely to significantly reduce the strength of natural sinks, making the task of merely stabilising the atmospheric concentration of CO_2 more difficult. Due to these factors, decreasing the atmospheric concentration of CO_2 in order to stay on an overshoot trajectory is likely to require emissions to be reduced to a small fraction of current emissions. How far emissions would have to fall, and how quickly the atmospheric concentration of CO_2 would decline, are unknown. There is a risk that emissions would not be able to be reduced to sufficiently low levels in the required period of time, and that the atmospheric concentration of CO_2 would not fall at the necessary rate.

Following an overshoot strategy involves a risk transfer to future generations. The scientific uncertainty associated with normal stabilisation trajectories is magnified, along with the risk of exceeding thresholds for DCC. Attempting overshoots may ultimately be necessary in the future due to inadequate short- and medium-term abatement. Using methane as the basis of an overshoot strategy is probably the most realistic option due to its relatively short atmospheric lifetime (approximately 12 years). However, any deliberate attempt to employ such a strategy in the near-term in order to reduce abatement costs could be hazardous. The strategy presumes that in the latter part of the 21st century there will be the technological options, political will and near universal compliance necessary to reduce emissions to levels close to zero. There is also a dubious assumption that humanity will be able to accurately identify and avoid thresholds for dangerous impacts. If an overshoot strategy is employed, decision-makers should explicitly identify the degree of uncertainty associated with the trajectory and the risk that thresholds for DCC will be exceeded and that the impacts may be irreversible.

7. Conclusion

The data from the HSM, UVic and BERN climate-carbon cycle models suggest there is little chance of meeting the Australian Prime Minister’s 450 – 490 ppm CO_2-e concentration target. If the data are correct, atmospheric concentration targets below 550 ppm CO_2 (~650 ppm CO_2-e) will be difficult to achieve without a radical shift in the international political landscape in the next few years.

In order to have a reasonable chance of keeping the increase in the global average surface temperature to 2 – 3°C above pre-industrial levels, developed countries are likely to have to pursue sharp emission reductions over the coming two decades. Developed country mitigation targets of 60 per cent below 2000 levels by 2050 are likely to fall far short of what is required to meet these global temperature targets. To prevent the atmospheric concentration of CO_2 exceeding 550 ppm, developed countries must provide developing countries with additional space within the global emission budget.

While deep cuts in developed country emissions are required to meet 2 – 3°C temperature targets, developing country emissions must also be quickly stabilised and reduced. If the emission trends since 2000 continue for much longer, the growth in developing country emissions will close off the option of keeping the atmospheric concentration of CO_2 below 550 ppm.

Research is being undertaken to provide additional information on the likely strength of climate-carbon cycle feedbacks and the emission budgets that are consistent with certain atmospheric concentration levels. The results from this research may be included in the fifth assessment report of the IPCC, which is not due for publication until at least 2013. In the meantime, negotiations are continuing on the post-2012 climate regime and countries like Australia are attempting to make decisions on the design of important mitigation mechanisms. Data from the existing coupled climate-carbon cycle models should be used in these processes. Failure to base current abatement decisions on the most recent data from these models could result in mitigation targets being set too low. Path dependencies can create significant lag times in policy processes. If the data from existing coupled climate-carbon cycle models is ignored in current policy processes, future options to avoid DCC may be closed off.

Appendix A Annual emission indices for HSM and BERN

Table A1 Annual emission indices for HSM and BERN 450 ppm coupled budgets, 1990 – 2050, assuming 2000 as base year

	1990	**2000**	**2020**	**2030**	**2040**	**2050**
HSM 450 ppm						
Global	91	100	124	69	16	8
A1	103	100	20	4	4	4
NA1	82	100	202	118	25	11
BERN 450ppm						
Global	91	100	152	120	84	55
A1	103	100	85	33	12	9
NA1	82	100	202	185	138	88

Table A2 Emission reduction indices for HSM and BERN 550 ppm coupled budgets, 1990 – 2050

	1990	**2000**	**2020**	**2030**	**2040**	**2050**
HSM 550 ppm						
Global	91	100	157	137	106	77
A1	103	100	97	62	29	12
NA1	82	100	202	193	164	126
BERN 550ppm						
Global	91	100	159	149	134	117
A1	103	100	102	83	59	39
NA1	82	100	202	199	190	175

Appendix B Annual emission indices for HSM and BERN for Annex I 60 per cent mitigation scenario

Table B1 Annual emission indices for HSM and BERN 450 ppm coupled budgets, 1990 – 2050, under Annex I 60 per cent mitigation scenario, assuming 2000 as base year

	1990	2000	2020	2030	2040	2050
HSM 450 ppm						
Global	91	100	155	38	30	23
A1	103	100	92	75	57	40
NA1	82	100	202	10	10	10
BERN 450ppm						
Global	91	100	155	127	76	43
A1	103	100	92	75	57	40
NA1	82	100	202	165	90	45

Table B2 Annual emission indices for HSM and BERN 550 ppm coupled budgets, 1990 – 2050, under Annex I 60 per cent mitigation scenario, assuming 2000 as base year

	1990	2000	2020	2030	2040	2050
HSM 550 ppm						
Global	91	100	155	140	111	77
A1	103	100	92	75	57	40
NA1	82	100	202	189	151	105
BERN 550ppm						
Global	91	100	155	146	133	117
A1	103	100	92	75	57	40
NA1	82	100	202	199	190	175

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